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ENGINEERING FEASIBILITY STUDY OF ULTRASONIC APPLICATIONS FOR AIRCRAFT MANUFACTURE

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Areas in which ultrasonic energy can be effectively applied in production metal-working processes, particularly in the manufacture of Army helicopters and light aircraft, were explored. Literature covering ultrasonic applications in various metal forming, metal removal, and metal joining processes was thoroughly reviewed to establish, in each case, the present status and the potential in terms of cost effectiveness and product improvement. An annotated bibliography is included in an appendix.

Several leading Army aircraft manufacturers were surveyed to examine specific metalworking problems that might be solved by ultrasonic application, and analyses were made to indicate potential benefits and cost savings in these areas.

Production equipment and techniques were found available for ultrasonic tube drawing and ultrasonic drilling of composite materials. Production engineering was recommended for several processes of short-range applicability: ultrasonic welding, swaging, turning, boring, twist drilling, broaching, torque wrenching of small fasteners, press fitting, and tube flaring. Other ultrasonic processes of long-range applicability were recommended for further investigation and possible development: drawing and straightening of rotor spars, forming of chafing strips, milling, thread cutting, diffusion bonding, wrenching of large fasteners, forging, extrusion, and powder metallurgy processing.

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Extrusion						
Rolling						
Forging						
Swaging						
Riveting						
Stretch Forming						
Metal Flaring						
Dimpling						
Straightening						
Metal Bending						
Powder Metallurgy						
Turning (Machining)						
Boring						
Drilling						
Milling (Machining)						
Broaching						
Thread Cutting						
Grinding (Material Removal)						
Metal Finishing						
Ultrasonic Welding						
Diffusion Welding						
Wrenching						
Press Fitting						
Ultrasonic Soldering						
Fusion Welding						

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by

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Aeroprojects Incorporated
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DEPARTMENT OF THE ARMY
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FOREWORD

This summary report on the feasibility of applying ultrasonic energy to metalworking processes of significance in the manufacture of Army helicopters and light aircraft was prepared by Aeroprojects Incorporated, West Chester, Pennsylvania, under Army Contract No. DAAJ01-72-C-0737(P1G), AMS Code 1497, Project 1728037. The work was carried out under the sponsorship of the U.S. Army Aviation Systems Command, St. Louis, Missouri, with Mr. John Gassner of USAAVSCOM serving as Contracting Officer's Representative.

This project was funded under the U.S. Army Manufacturing Methods and Technology (MM&T) Program, which has as its goal the development of new and improved manufacturing methods, processes, and techniques in support of the production of Army Materiel.

In support of this work, visits to representative aircraft companies were made primarily by Mr. J. Byron Jones, President, and Mr. Philip C. Krause, Assistant to the President, of Aeroprojects. Messrs. Jones and Krause also provided insight in evaluating the potential of the various ultrasonic processes. Acknowledgement is made of the contributions of Mr. James D. Anderson, Ferris State College, Big Rapids, Michigan, who assembled the information and provided the cost effectiveness studies presented in Appendix A. Appreciation is also expressed to Branson Sonic Power Company, Danbury, Connecticut, for providing the photographs of Figure 7.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

This study was undertaken to explore areas in which sonic and ultrasonic energy can be effectively applied in production metalworking processes, particularly in the manufacture of Army helicopters and light aircraft. The areas of specific interest include ultrasonic metal forming, ultrasonic metal removal, and ultrasonic metal joining.

A. Significance of Investigation

Recent attention has been focused on the skyrocketing costs of military aircraft, reflecting increased performance and sophistication as well as inflationary pressures that have driven up material and labor costs. Major effort is being directed toward reducing costs without sacrifice in aircraft performance and reliability, and the "design to cost" philosophy has become the guiding principle in all aircraft manufacture.

Accordingly, the Army is scrutinizing all aspects of initial fabrication costs of aircraft, as well as life cycle costs as reflected in serviceability and maintainability. Conventional processing techniques are being examined to determine if there are ways to make a part or an assembly faster in order to reduce manpower requirements, with less scrap loss to reduce material costs, and/or with lower capital equipment investment to reduce depreciation and overhead costs.

Ultrasonic application in various metalworking processes has the potential for reducing costs with concomitant improvement in product quality, but this potential has not been adequately explored nor implemented for the aircraft industry.

Literature over the past 30 years has lauded the actual or potential benefits of ultrasonic metal processing, sometimes in glowing and sometimes in guarded terms. Industrial observers and potential users have generally been slow to recognize these claims and accept this new technology, often with some justification.

In a few areas, enterprising aircraft engineers have ventured into ultrasonic processing only to find that it does not provide an instant solution to their problems and that there are unresolved difficulties that appear too costly and time-consuming to pursue. The process may thus be rejected on the basis that the anticipated benefits do not appear to be worth the effort involved. The result is a "pie in the sky" attitude toward many of the claims and a resistance to more thorough evaluation.

On the other hand, ultrasonic investigators have often been intent in carrying out small-scale feasibility studies in the confines of their laboratories without an appreciation of manufacturing problems and without coming to grips with the task of translating their efforts into specific hardware for industrial use or providing hard data on the cost effectiveness of a process.

In spite of these handicaps, progress has been made. By the mid-1950's, several ultrasonic processes had received limited acceptance in industry, particularly ultrasonic soldering, slurry machining, cleaning, and nondestructive testing. Additional applications in limited production use today, although not necessarily in the aircraft industry, include ultrasonic welding, tube drawing, non-slurry machining, certain types of deburring and finishing operations, and a variety of low-power applications involving measurement and detection.

Industrial activity has been spurred to some extent by the interest* of the Materials Advisory Board of the National Academy of Sciences (now National Materials Advisory Board) and by the Metalworking Processes and Equipment Program (MPEP), an inter-agency program involving Army, Navy, Air Force, and NASA, concerned with the development and implementation of new techniques for deforming metals, particularly the newer high-strength and refractory metals and alloys that resist conventional processing. Under this program, work has been sponsored in ultrasonic rolling, wire, rod, and strip drawing, draw ironing, extrusion, and machining, as well as basic studies in ultrasonic metal deformation. In most of these instances, however, economic feasibility has not been established, and the results have not been translated into production-type hardware useful to industry.

This study attempts to provide a realistic appraisal of the potentialities of ultrasonic application in metal forming, metal removal, and metal joining processes, with a view to determining where the trade-offs favor the use of these techniques. The effort has involved a survey of past technical achievements in each area and an appraisal of its present status with regard to industrial utilization; evaluation of the ultrasonic technology in terms of immediate and long-range applicability to existing problems in aircraft manufacture; examination of the cost effectiveness of such processes for specific applications; and recommendations for implementation of these processes.

B. Potential Areas for Ultrasonic Application

At the outset of the study, the metalworking areas for consideration were limited by contract definition and through discussions with USAAVSCOM personnel to those involving:

1. Processing of metals in the solid state, specifically by metal forming, metal removal, and metal joining.

* "Metalworking Processes and Equipment," Publication MAB 206-M (7), Materials Advisory Board, National Research Council, National Academy of Sciences, Washington, D. C., September 1968. Also T. F. Kearns, "MPEP--The Metalworking Processes and Equipment Program," Metals Engineering Quarterly, Vol. 4, May 1964, p. 1-11.

2. Vibratory frequencies above about 5000 hertz, in the upper sonic and ultrasonic ranges.*

3. High vibratory power levels, wherein ultrasonic energy is used to perform work.

4. Potential applications in the fabrication and assembly of Army aircraft (light fixed-wing aircraft and helicopters) specifically related to the air frame, rotor or propeller system, transmission system, controls, and landing gear.

Thus the following areas are specifically excluded from consideration:

1. Molten metal processing, as in melt casting.

2. Processing of nonmetallic materials such as ceramics and plastics, except where the same ultrasonic process is effective for both metallic and nonmetallic materials. Thus we have excluded such processes as slurry machining, effective primarily for ceramics and other brittle materials, and ultrasonic welding of plastics, which operates by a different mechanism from ultrasonic welding of metals.

3. Ultrasonic cleaning.

4. Ultrasonic applications involving measurement and control, such as nondestructive testing, thickness measurement, material property measurement, and the like.

5. Low-frequency applications, usually involving frequencies of a few hundred hertz. Such frequencies have been found useful for certain applications, such as vibratory finishing, stress relief, upsetting, forging, and arc welding, but these are included only insofar as they suggest analogous ultrasonic processes.

6. Potential applications for aircraft avionics, ordnance, and engines, as in ultrasonic welding, soldering, or drilling in electronics assembly or ultrasonic ring-weld encapsulation of ordnance devices.

Within the limitations thus imposed, all available literature on ultrasonic processing was assembled and carefully reviewed, and pertinent references were abstracted. The abstracted references are included as Appendix B.

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* For convenience, the type of processing covered in this work is referred to as ultrasonic, even though the actual frequencies may fall below this range. In practice, most frequencies used are ultrasonic because of the noise factor with frequencies in the audible range.

From this literature review, from discussions with personnel of other organizations, and from our own experience and knowledge in ultrasonic metal-working, we have compiled a list, presented in Table I, of metal forming, removal, and joining processes wherein ultrasonic application has shown actual or potential beneficial effects.

Table I

POTENTIAL AREAS FOR ULTRASONIC APPLICATION

Metal Forming	Metal Removal	Metal Joining
Tube Drawing	Turning	Ultrasonic Welding
Wire Drawing	Boring	Diffusion Bonding
Rod Drawing	Core Drilling	Wrenching
Section Drawing	Twist Drilling	Press Fitting
Extrusion	Milling	Soldering
Rolling	Broaching	Brazing
Forging	Reaming	Fusion Welding Resistance Welding
Swaging	Thread Cutting	Arc Welding
Coining	Grinding	
Rivet Upsetting	Sawing	
Stretch Forming	Planing	
Tube Flaring	Shaping	
Dimpling	Finishing Polishing	
Draw Ironing	Honing Lapping	
Straightening and Bending	Deburring	
Powder Metallurgy Processing		

With certain of these processes--ultrasonic tube drawing, wire drawing, tube flaring, core drilling, ultrasonic welding, soldering, and brazing--production application has been achieved, although some applications engineering may be required to further extend use of the process. For other processes, prototype equipment has been evolved and successfully demonstrated, but actual production processing has not yet been achieved. Still other processes have shown promising results on a laboratory scale, but further research and/or development, as well as applications engineering, is required to achieve production utilization.

Section II of this report provides background summaries for many of the processes listed in Table I, defines the present status of each, and indicates its potential in terms of cost savings and product improvement.

C. Aircraft Industry Survey

To provide meaningful orientation to this study, visits were made to several leading manufacturers of Army helicopters and light aircraft to explore problem areas which may be amenable to solution by ultrasonic processing, as well as other metalworking areas wherein production may be facilitated by ultrasonic application. The results of this survey, discussed in detail in Section III, indicate the universality of certain problems, reveal substantial interest in the ultrasonic potential for solving some of these problems, and underline specific areas of major importance.

The ultrasonic processes listed in Table I have accordingly been grouped to reflect the interest of the aircraft industry. Table II indicates areas of major interest, of minor interest, and of little or no interest. The evaluations included herein place greatest emphasis on the areas of major interest, although other processes that appear to have long-range potential also receive consideration.

D. Cost Effectiveness Studies

Consideration has been given to potential cost savings that can be achieved by substituting an ultrasonic process for an existing one or by using ultrasonic energy as an assist to a conventional process. Generally the cost savings can be attributed to one or more of the following factors:

1. Increased processing rates. Accelerated metal forming and metal removal under ultrasonic influence, for example, have been repeatedly demonstrated, and production unit cost savings with this factor alone can be substantial.

2. Reduced force requirements, so that lower capacity machines can be used or a machine of a given capacity can be used for a broader range of applications, thus effecting savings in capital equipment investment.

Table II

AREAS OF INTEREST EXPRESSED BY AIRCRAFT COMPANIES IN ULTRASONIC PROCESSING

	Major Interest	Minor Interest	Little or No Interest
Metal Forming	Swaging Tube Drawing Section Drawing Straightening Tube Flaring	Tube Bending Riveting Dimpling	Wire Drawing Rod Drawing Draw Ironing Coining Rolling Forging Extrusion Powder Metallurgy
Metal Removal	OD Turning ID Boring Twist Drilling Finishing	Milling Broaching Core Drilling Thread Cutting	Reaming Grinding Sawing, Planing
Metal Joining	Ultrasonic Welding Weld Bonding Diffusion Bonding Wrenching Press Fitting	Soldering Brazing	Fusion Welding

3. Elimination of discrete process steps. In tube drawing, for example, it has been shown that a three-draw operation may be reduced to two draws with ultrasonics or that certain intermediate annealing operations may be eliminated. In metal removal, the altered surface finish may eliminate or minimize the necessity for certain finishing operations. In ultrasonic fluxless soldering and brazing, the necessity for subsequent cleaning for flux removal is eliminated.

4. Extended tool life. In metal removal operations, effective tool life may be extended severalfold when the tool is ultrasonically activated, so that machine downtime for tool changes is substantially reduced.

5. Fewer rejected parts or assemblies. With the improved product quality achieved with ultrasonic processing, material and labor costs that go into producing components subsequently found to be unacceptable can be sharply reduced.

6. Extended service life of component or assembly and/or reduced maintenance. For example, the bolt head corrosion problem requires constant surveillance, and detailed inspection procedures are prescribed for critical bolted assemblies; an ultrasonically ring-welded metal patch over the bolt head, to replace currently used protective coatings, would provide a hermetic seal of greatly extended life, with substantial reduction in maintenance costs.

Cost savings emanating from the above would of course be offset to some extent by costs associated with introducing ultrasonic processes into production operations: ultrasonic equipment costs; costs of modifying conventional machines to accept ultrasonic systems where this is possible; costs of special tooling; and costs of developing and/or engineering the ultrasonic process to the production stage in areas where production techniques and tooling are not yet available.

In order to obtain a more specific indication of potential cost savings, we retained the services of Mr. James D. Anderson, Machine Tool Department, School of Technical and Applied Arts, Ferris State College, Big Rapids, Michigan, who has had significant experience in aircraft and helicopter manufacturing, particularly at North American Aviation and Hughes Tool Company.

Mr. Anderson assembled cost information, insofar as it could be made available, on some operations of urgent concern to several of the aircraft companies and evaluated potential time and cost savings that could be effected with ultrasonic processing. The operations covered were in the areas of ultrasonic welding, swaging, drilling, press fitting, and wrenching. A summary of his work is included as Appendix A.

II. SURVEY OF ULTRASONIC METALWORKING PROCESSES

As indicated in the literature review of Appendix B, there has been much examination and experimentation in ultrasonic application to the whole range of metalworking processes. A few of these ultrasonic applications have achieved production status; others have reached an advanced state of development and production use is imminent; still others require further experimentation and development to establish their effectiveness as a production tool, although technical benefits may be apparent.

It should be observed that ultrasonics may not always be an effective adjunct to a metalworking process nor does it solve all metalworking problems. In some instances the projected benefits are highly speculative and may be incapable of realization in a production environment, at least in the present state of the technology. Perhaps the benefits are small and do not justify development or equipment costs; perhaps ultrasonic power requirements are beyond the capabilities of existing or presently projected ultrasonic equipment; perhaps the problem of coupling the ultrasonic energy into the work area presently appears insurmountable. Application and use of this new technology must be selective.

The evidence indicates, however, that ultrasonics is and can be an effective production tool for many applications. The years of research and development have paid off. We have learned much of the basic mechanisms of ultrasonic effects on metals and of how to transmit the energy effectively into metals. Concomitantly, there have been engineering advances related to the development of highly efficient ultrasonic generating, transducing, and transmitting systems that contribute to economic feasibility.

The basic requirements of any ultrasonic system are: the frequency converter, which converts ordinary 60-hertz electrical line power to the frequency of operation; the transducer, which converts the high-frequency electrical power from the converter into high-frequency mechanical vibration; and the coupling system, which transmits the vibratory energy from the transducer to the work. Recent developments in all of these areas have given strong impetus to production use.

Solid-state frequency converters of the silicon-controlled rectifier (SCR) or transistorized types provide substantial advantages over the older electron-tube and motor-generator types. In comparison, the solid-state devices are smaller, more compact, lighter in weight, and easier to maintain. More significant is the fact that these devices have approximately 90 percent conversion efficiency, compared to about 50 percent for the electron-tube converters. An ancillary development is that of automatic frequency control for precise system matching during the varying conditions of a process cycle.

Conversion of electrical to vibratory power has been greatly facilitated by the development of highly efficient transducer assemblies incorporating disks of advanced electrostrictive ceramic compositions such as lead zirconate titanate. Until recently, the most satisfactory transducers were

laminated nickel stacks, which are rugged and durable and can withstand high temperatures and some degree of overloading. Their efficiency is low, however, and only about 25-35 percent of the input electrical power is converted to acoustical output power. The new ceramic transducers, designed into rugged, compact, relatively inexpensive assemblies, have electromechanical conversion efficiencies of 75 percent or higher, so that substantially lower electrical input power is required to achieve equivalent acoustical output.

Acoustical coupling systems, which serve as links between transducer and work area, have also been developed to a state of high efficiency through intensive evaluation of materials of construction and geometry. Effective materials include stainless steel, K-Monel, aluminum-bronze, beryllium-copper, and 6Al-4V titanium alloy because they withstand high cyclic and static stresses, permit reasonable acoustic impedance match with other components, and exhibit low vibratory energy loss. The geometry of such systems is dependent on end-item use.

It is now generally recognized that any ultrasonic system, to achieve maximum effectiveness, must be designed specifically for its end use. Historically, much experimentation has been nonproductive because "generalized" equipment was used and not enough attention was paid to acoustic impedance matching into the work material. The work-contacting tool, which terminates the coupling system, requires the same meticulous acoustic design consideration as any other member of the acoustic energy train.

A recurrent problem has been evident in many applications involving transmission of ultrasonic energy into metals under high static loads. Frequently a transducer is noted to "stall" when loads of more than a few pounds are applied through the systems. Various nodal mountings and other arrangements have been used in an effort to minimize this problem. It has become evident that high-power ultrasonic transmission requires the use of force-insensitive mounting systems which prevent vibratory energy loss to the support structure and minimize frequency shift under such conditions. The mount is essentially an axially resonant member, often a sleeve metallurgically attached to the transmitting coupler at one end and with the opposite end free. With high acoustic impedance into air at the free end, almost complete wave reflection occurs; a true vibratory node is produced at the point of attachment, and an antinode, with maximum vibratory amplitude, at the terminus of a properly designed coupling system. Such force-insensitive mounts have been effectively used with static loads of several hundred tons.

The above equipment developments are largely responsible for the emergence of some aspects of ultrasonic metalworking from the laboratory into actual or imminent production usage.

It should be noted that in these processes the vibratory frequency *per se* is not usually a controlling parameter. Essentially equivalent results have been obtained over the range from 15 to 75 kilohertz, and higher or lower frequencies appear to show no markedly different effects. Frequency, however, does govern the size of the transducer, and the higher frequencies may be indicated where physical space or weight restrictions dictate a smaller transducer-coupling system. Conversely, the larger vibratory

amplitudes associated with the lower frequencies may be desirable for certain applications.

Vibratory power, on the other hand, is an important variable in any application. Usually there is a lower power threshold below which no significant effect is obtained. There is also frequently an upper limit beyond which vibratory energy may damage a workpiece. This parameter needs to be examined for any given application.

In the following pages, each of the various metalworking processes is examined with regard to its present status, mechanism of operation, equipment requirements, observed effects, and actual or potential benefits for industrial use.

A. Metal Forming

The areas of metal forming in which ultrasonic application has provided useful effects include both tension and compression forming process: drawing of tubing, wire, and rod; stretch forming such as deep drawing, draw ironing, tube flaring, and dimpling; forging-type processes such as upsetting, closed die forging and swaging; primary metal working by rolling or extrusion; bending and straightening; and powder metallurgy consolidation processes.

Ultrasonic effects in facilitating such forming processes have been attributed to two major phenomena: increased metal plasticity and reduced friction between the tool and the workpiece. The extent to which each contributes has not been determined quantitatively, and it is possible that the relative significance differs for different forming processes.

The discovery that metals deform more readily with ultrasonic excitation dates back to the mid-1950's,* when experimentation in tensile stressing of fine metal wires under vibratory influence showed substantial reduction in the yield strength and increase in elongation of the wire. The magnitude of the effect was independent of frequency but increased linearly with increasing vibratory power or amplitude. This phenomenon is attributed to ultrasonically facilitated formation and movement of dislocations within the crystal lattice structure so that intercrystalline slip can take place more readily.

The friction-reducing effect of ultrasonics can be surmised by tactile sensation: an ultrasonically excited coupler or tool feels slippery to the touch. This phenomenon has been demonstrated independent of the plasticity effect, as for example in the assembly of close-tolerance parts or the torque-tightening of threaded fasteners. Reduction of frictional forces normally acting between a forming tool, such as a die or punch or roller, and the workpiece facilitates the forming process primarily by reducing the force required for deformation.

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* Literature on this phenomenon is not included herein but is reviewed rather extensively in Refs. 5 and 16 in Appendix B.

The results of the reduced friction and increased plasticity, in addition to reduced force requirements, are generally evident in terms of increased processing rates, increased deformation per pass, and possible elimination of one or more processing steps, all of which effect savings in processing costs. In addition, product quality may be improved as with closer tolerances, improved surface finish, and/or improved mechanical properties. Specific advantages for each process are indicated in the discussions below.

1. Tube Drawing (Refs. 19-40, P16, P24-P27, P29, P31, P33)

Since the earliest known work in ultrasonic tube drawing in the early 1960's, this process has made rapid progress and is being effectively used in production with reported substantial time and cost savings. Initially developed for drawbench drawing with an ultrasonically activated plug, it has also been applied to bull block drawing with ultrasonic die activation.

In plug drawing, which involves drawing of tubing over a plug or mandrel supported at the end of a back support rod (of suitable length for the tube being drawn), the ultrasonic energy is transmitted longitudinally through the back support rod, with the transducer-coupling system screw-attached at the rod end opposite the plug. For effective transmission, the rod/plug assembly must be tuned and impedance-matched to the transducer-coupling system frequency. Such systems can be installed on conventional drawbenches with minor modification, generally involving only a means for supporting the transducer-coupling assembly at the end of the bench and acoustical design of the rod and plug. Ultrasonic plug drive systems are available in multiples so that, for example, one rod can be loaded while another is being drawn.

In ultrasonic die drive systems, vibratory energy from the transducer is usually transmitted through a curved wave guide system (providing clearance for the drawing operation), which terminates in a die holder into which interchangeable dies are threaded and locked. The die is thus excited in a longitudinal mode. Such a system may be installed on a standard drawbench, possibly even in conjunction with an ultrasonic plug drive system, or on a bull block for continuous drawing of small-diameter tubing.

A number of production benefits have been reported by users in terms of both reduced costs and higher quality tubing:

a. Reduction in required draw force, usually in the order of 20-40 percent, but sometimes as high as 75 percent, so that there is less hazard of tensile fracture of the tubing.

b. Increased cross-sectional area reduction per pass so that fewer passes are required to achieve a given size.

c. Possibly elimination of one or more interdraw anneals.

d. Increased drawing rates, particularly with materials normally difficult to draw.

e. Elimination of stick-slip and chatter, resulting in smoother drawing and prolonged tool life.

f. Minimized lubricant breakdown and possible use of lower grade lubricants.

g. Smoother surface finish. With ultrasonic plug drive, ID finishes of 3-8 microinches are reproducibly obtained; 16 microinches is considered exemplary with non-ultrasonic drawing.

h. Improved dimensional control over long lengths.

i. Increased diameter-to-wall thickness ratios. Whereas 50:1 is about maximum in non-ultrasonic drawing, ratios up to 500:1 have been achieved with ultrasonic activation.

j. Ability to draw from round to complex shapes in a single pass.

k. Sharper corner radii for angular-section tubing.

l. No residual effect on microstructure or mechanical properties.

Various of these effects have been achieved in production processing of tubing ranging from hypodermic needle size to about 2-1/2 inches diameter by 1/4-inch wall thickness. Processed materials include common metals such as aluminum, copper, and steel, as well as more exotic and difficult-to-draw materials such as titanium, niobium, Zircaloy, beryllium-copper, cupro-nickel, Monel, and phosphor-bronze. Reported savings in processing time and cost range up to 35-40 percent.

The greatest effectiveness of the process has been found in the drawing of tubing that is difficult or impossible to cold-draw by the usual techniques, as in thin-wall or complex-shaped tubing, or in the manufacture of tubing that must meet stringent design requirements, as for aerospace and nuclear applications, pressure and instrumentation tubing.

2. <u>Wire Drawing</u> (Refs. 41-68, P14, P15, P17-P24, P28, P30-P32)

Ultrasonic wire drawing, first described in a patent filed in 1944, has been investigated extensively, and production use has been established. Its basic mechanisms are the same as for tube drawing--reduced friction between the wire and the draw die and possibly also increased metal plasticity--and many of the same beneficial effects are achieved.

The process involves ultrasonic activation of the draw die. Longitudinal, torsional, and transverse modes with reference to the wire axis have variously been investigated; greatest effects are generally obtained with the longitudinal mode. Usually drawing is carried out in air with an applied lubricant, but a recently developed technique, said to be used in production at rates up to 2000 feet per minute, involves drawing through one or more dies immersed in a liquid lubricant which simultaneously cleans the wire and

prevents accumulation of debris at the mouth of the die. As with tube drawing, mounting of ultrasonic systems on conventional wire drawbenches is feasible.

Reported benefits of ultrasonic wire drawing over conventional drawing include:

a. Substantially reduced draw forces, which may range up to 75 percent reduction at the lower draw speeds. This effect increases with increasing ultrasonic power and decreases with increasing draw speed.

b. Increased area reduction per pass. In a wet drawing operation, copper wire of 0.01-inch diameter was reduced to 0.003 inch through 9 consecutive dies; 14 dies were required for non-ultrasonic drawing.

c. Reduced wire breakage especially with fine wires of brittle materials.

d. Facilitated drawing of difficult-to-draw materials and elimination of the necessity for cladding the wire prior to drawing. For example, beryllium wire, which is ordinarily nickel-clad and drawn warm, was ultrasonically cold-drawn in continuous lengths without cladding from 0.005 inch to 0.001 inch in successive draws.

e. Reduced die heating and wear.

f. Improved surface finish and more uniform wire diameter.

g. Possibly more homogeneous and finer-grained metallurgical structure.

h. Increased ductility in the drawn wire and with probably negligible effect on its tensile strength (increases, decreases, and no change in tensile strength have variously been reported).

Ultrasonic techniques have been effectively used in drawing wires of aluminum, copper, steel, nickel, lead, tin alloy, titanium, and molybdenum. Production drawing is economically feasible because of relatively low ultrasonic power requirements and because existing drawbenches can be equipped for ultrasonic activation with some modification.

It is anticipated that production use of the process will be extended. One potential application, not mentioned in the literature, is for drawing fine wires of boron, etc. used in the fabrication of fiber-reinforced composite materials.

3. Rod and Section Drawing (Ref. 55)

Although ultrasonic drawing of rods and other elongated workpieces of constant cross section has received only minor experimental consideration, these processes offer the same potential as ultrasonic tube and wire drawing: increased drawing rates, reduced draw forces, greater reduction per pass, minimized chatter and stick-slip, drawing of otherwise difficult-to-draw materials, etc. Activation of the draw die is involved, at least for solid cross sections, but ultrasonic power requirements could be considerably higher than for tube or wire drawing, depending on cross-sectional area.

Further development is required to determine the interaction of ultrasonic and processing variables; economic feasibility will need to be established; and a survey must be made to determine potential applications in industry.

4. Extrusion (Refs. 69-73, 117, 130, P34-P37)

Experimentation and some limited pilot plant work has indicated that ultrasonic extrusion offers substantial potential for fabricating parts from both bulk and powdered metals.

Extrusion of bulk metals (aluminum, lead, copper, and brass) has been carried out at suitably elevated temperatures with ultrasonic activation of the die, ram, or cylinder; most effective results are obtained with die activation. The benefits include:

a. Extrusion rate increases up to about 300 percent and/or force reductions of up to 50 percent.

b. Reduced friction between work material and tooling and improved metal flow.

c. Higher extrusion ratios.

d. Improved effectiveness of lubricants.

Extrusion of powdered metals evolved from earlier work in ultrasonic extrusion of ceramic powders usually mixed with plasticizer and water. Die activation was used, at times also with mandrel activation in extrusion of hollow objects. Demonstrated advantages of such processing include:

a. Extrusion rate increases up to several hundredfold and/or force decreases up to about 90 percent.

b. Reduced plasticizer and water content, with effective extrusion of mixes too stiff for conventional extrusion.

c. Increased green density and strength from closer particle packing so that handling of the extrudate before plasticizer burn-out and sintering is facilitated.

d. Improved surface finish, free from tears and cracks.

e. Improved concentricity with tubular members.

This technique was used for the experimental fabrication of cupro-nickel tubing which, after sintering, was ultrasonically cold-drawn to the required size. Density of the final product was 98-99 percent of theoretical, and strength was equivalent to that of the wrought product. Economic analysis of the process indicated production costs at least competitive with those of equivalent wrought tubing. Refinements of the process are required for full-scale production application.

Both bulk metal and powder metal extrusion with ultrasonic application appear practical and economical for production use with further development. Ultrasonic systems for either die or mandrel activation can be installed on modified conventional extrusion presses.

5. Rolling (Refs. 74-83, P38-P42)

Ultrasonic rolling has been investigated in only limited experimentation with wire flattening, ribbon rolling, and rolling of strip metal up to a few inches wide. The mechanism is the same as with other metal forming processes: reduced friction between the rolls and the material being worked, and increased formability of the material.

Various techniques have been used to activate the metal, and the literature indicates that the greatest range of experimentation has been carried out in Russia. One or both of the work-contacting rollers has been activated in the longitudinal, torsional, or radial mode, and the metal sheet itself has been excited to vibration via the tension device for pulling the strip between the rolls.

Claimed advantages, demonstrated with aluminum, copper, steel, and lead strip material and with zinc and molybdenum wires, are:

a. Decreased force requirement (up to 70 percent reduction) and/or increased thickness reduction.

b. Increased rolling rate.

c. Reduced heating, lubrication, and annealing requirements.

d. Reduced friction and wear on the roller bearings.

e. Decreased grain size and improved mechanical properties of the rolled material.

With the present state of ultrasonic technology, it is doubtful that ultrasonic rolling can be practical or economical except for relatively narrow strip or wire. The ultrasonic power and equipment requirements for standard wide sheet would probably not justify the improvements attainable. Even for strip materials, development costs will be substantial.

6. Forging (Refs. 84-96, P61)

Little investigation of ultrasonic forging has been carried out except for free upsetting of small specimens of aluminum, copper, steel, and lead, but the potential certainly exists for closed-die forging with an ultrasonically activated press, particularly in view of the results obtained with ultrasonic extrusion, which also involves metal compression.

Ultrasonic upsetting has been demonstrated to effect:

a. Substantially reduced upsetting forces. In one investigation it was noted that with sufficient vibratory intensity the pressure could be reduced essentially to zero.

b. Reduced upsetting temperatures.

c. Increased effectiveness of lubricant.

d. Increased homogeneity and refined grain structure in the upset specimen.

e. Increased hardness and freedom from porosity.

Here again the effects were attributed to reduced friction and increased metal plasticity.

Although substantial development effort will be required to realize these benefits for closed-die forging, there appears to be real potential for producing superior forgings of relatively small parts, free from cracks and residual stresses so that longer service life can be anticipated. Because of the decreased force requirements, smaller presses could be used or press capacity increased.

One forging-like operation that offers the possibility of more immediate use is swaging, for example, of tubes onto end fittings. Usually relatively small metal masses are involved, and ultrasonic activation of a swaging tool could improve metal flow into grooves and threads to provide a stronger, more durable assembly.

7. Rivet Upsetting (Ref. 97-103, P59, P63)

Experimentation within the past few years has shown considerable effectiveness with ultrasonic excitation during upsetting of rivet heads, with such benefits as:

a. Reduced force requirements in the range of 50:1 to 100:1.

b. Greater head height reduction.

c. Improved shank expansion and hole fill, perhaps with actual bonding in the joint around the shank.

d. Freedom from cracking and splitting of the rivet head.

e. Increased joint strength.

Such effects have been demonstrated with rivets of up to 5/16-inch diameter of aluminum, titanium, and steel.

In at least some of the investigations, ultrasonic systems for this operation were installed on commercial riveting equipment, transmitting vibratory energy axially through the rivet. The force reductions are said to permit smaller, lighter, simpler, and less expensive equipment, less cumbersome to operate. Portable ultrasonic riveters for use in the field appear feasible. The improved quality of the joint, increased operating facility, and equipment cost savings, as well as the possibility of noise abatement with ultrasonic operation, suggest that further development into a production technique would be profitable.

8. Stretch Forming (Refs. 104-112, P10-P13, P56-P58)

Various forming operations, including dimpling, tube flaring, deep drawing, and draw ironing have been facilitated by ultrasonic activation of the forming tool in either an axial or a torsional mode. Such processing has been used with alloys of aluminum, copper, steel, nickel, and titanium.

Both cost savings and product improvement have been demonstrated in terms of:

a. Reduced force requirements and/or increased deformation.

b. Elimination of one or more processing steps, such as draw passes or intermediate anneals.

c. Possibility of forming to geometries otherwise difficult to achieve in a given material.

d. Elimination of cracks, splits, ripples, or other imperfections.

e. Improved surface finish.

f. Closer dimensional tolerances.

In dimpling of aluminum and titanium alloy sheet up to 0.040 inch thick, dimples produced at room temperature with an ultrasonically activated die were "at least as good" as those obtained with a non-activated but heated die. These results were obtained in spite of recognized vibratory damping difficulties (apparently a force-insensitive mounting system was not used), and the investigators considered it feasible to adapt existing dimpling equipment for ultrasonic activation.

Ultrasonic tube flaring to angles of from 30 to 90 degrees has frequently been used on a pilot-production basis with materials that are ordinarily difficult to flare without local heating or annealing. A

frequently used technique in ultrasonic ring welding involves flaring the mouth of a cylinder to a 90-degree angle to provide a flat flange for welding a closure thereto, followed by re-forming to a cylindrical geometry. With ultrasonic flaring, the flange material is not damaged even in the re-forming operation. In one application, aluminum and steel tubing was flared to the precise dimensions and surface finish required for spacecraft use, and excellent reproducibility was obtained.

With most of the stretch forming operations, the potential of ultrasonic application can be realized only with further development effort. Ultrasonic tube flaring, however, appears to require only production engineering oriented to specific end-item use.

9. Bending and Straightening (Refs. 113-114, P43-P47, P60, P62)

Sporadic investigations in ultrasonic bending and straightening indicate potential benefits in these areas in terms of achieving more permanent set in the material with less springback. This effect appears to involve increased metal plasticity and flow under ultrasonic influence, attributed to activation and migration of dislocations in the lattice structure, eventually forming locked lattice defects.

For example, ultrasonic application during tube bending is noted to promote metal flow from the inside to the outside of the bend so that wall thickening and thin-out are reduced. Application during coiling of coil springs eliminated the usual normalizing process. Less springback was measured when steel ribbons were bent or twisted with simultaneous ultrasonic activation. Integrally reinforced metal extrusions were more effectively straightened with contoured rollers when ultrasonic energy was applied, providing a smoother aerodynamic surface. Relief of internal stresses was observed to be a contributing factor.

Further investigation should be carried out in this area with respect to the mechanisms involved and the interaction of variables to produce the desired geometrical stabilization, and engineering development is required for a given application to establish equipment requirements.

10. Powder Metallurgy Processing (Refs. 115-130, P48-P55)

Since powder metallurgy processing is becoming recognized as a means for fabricating more or less complex parts without extensive machining and material scrap loss, the potential benefits of ultrasonic application in this technology become increasingly significant.

Current techniques usually involve blending of the metal powders, perhaps with the addition of a lubricant; compaction at high pressures into a preform approximating the end geometry; sintering; and hot forging or coining or finish machining to the final geometry. The consolidation step may involve hot pressing, cold pressing, extruding, roll compacting, or the like. All of these consolidation processes are improved by ultrasonic application.

Ultrasonics has been variously applied to the punch, ram, die, mandrel, or container in axial, transverse, torsional, or bell modes in processing a wide range of metal, ceramic, and cermet powders. Although much of the work in the United States has involved ceramic processing, applicability to metal powder processing has also been established. Stated advantages include:

a. Reduced temperature and/or pressure and/or time required to achieve a given density.

b. Reduced binder or plasticizer or lubricant content in the initial mix.

c. Increased green density and strength to facilitate handling of the preform before firing.

d. Increased density and strength after sintering.

e. Improved homogeneity with mixed powders.

f. Greater dimensional accuracy and stability.

g. Improved surface finish with less tearing and cracking.

These effects are usually attributed to reduced interparticle friction so that closer particle packing is achievable, as well as reduced wall friction. Interparticle bonding, removal of adsorbed gases from particle surfaces, and creep rate acceleration have also been mentioned as possible mechanisms.

Development effort will be required to evolve techniques and equipment for specific materials and end geometries, but such effort appears justified in terms of achieving the high product quality required for aircraft components.

B. Ultrasonic Metal Removal

Ultrasonic application to metal removal processes was first proposed in Germany in the late 1930's (Ref. P66), with claims of accelerated cutting and greater dimensional accuracy with lower applied forces than normally required, in such operations as turning, sawing, milling, planing, and boring. For the next 20 years there was little significant activity in this field except as described in patent literature. During this period, ultrasonic slurry machining of hard, brittle materials (omitted from this study) was evolved to production use, and out of this work came some equipment developments claimed to be applicable to other types of machining processes.

Since 1960, increasing attention has been given to single-point and multi-point cutting of materials with ultrasonically excited tools, and developments indicate that production use of such processes is imminent.

Although the results obtained have sometimes been contradictory, possibly because of different equipment setups and approaches, most current investigators agree that ultrasonic tool activation increases the rate of metal removal, reduces tool forces, increases tool life, eliminates machine chatter, and improves dimensional accuracy and surface finish on the machined part.

The mechanisms involved in achieving these effects have not been clearly established. One factor is certainly reduction in friction between the tool and the work material. There is possibly also local softening in the material just ahead of the tool, perhaps due to dislocation movements and/or localized heating, so that tool penetration is facilitated.

Extensive production use can be forecast for ultrasonic turning, boring, twist drilling and core drilling. Technical feasibility is unquestionably established, production-type equipment is available or imminent, and economic feasibility is being established. Other processes such as milling, broaching, and thread cutting offer substantial promise but will require further development before realistic appraisal of their potentialities can be made.

1. Turning and Boring (Refs. 137-152, P88-P91)

Within the last ten years, the benefits of ultrasonic activation of cutting during lathe turning and boring have been realized, and appropriate equipment has evolved through several generations to prototype production models for a limited range of applications.

Experimentation in various modes of activation of the cutting tool with respect to the workpiece has led to general agreement that the tool should vibrate into and out of the cut being made. With OD turning, this has resulted in a tool post providing tool activation in a direction tangential to the OD surface. With ID machining, the boring bar is activated in the torsional mode. Ultrasonic systems of both types are designed for mounting on the cross slide or compound of a standard engine lathe via an appropriate adapter plate.

Both faster processing and improved cutting characteristics have been variously reported. Negative results obtained in some early experimentation are probably attributable to the operating conditions used. Actually the process as applied to a given material involves complex interactions between ultrasonic parameters of vibratory mode and direction, power, and tool amplitude and standard operating parameters of cutting speed, depth of cut, and feed rate. The more recent work indicates the following effects to be achievable:

a. Increased rates of material removal.

b. Significant reductions in tool force (up to about 70 percent reduction).

c. Elimination or marked reduction in tool edge buildup.

d. Elimination of tool chatter.

e. Longer tool life.

f. Less heating of workpiece.

g. Improved surface finish, without the waviness and surface tearing that sometimes characterize non-ultrasonic cuts.

h. Chips characterized by greater curl radius, smoother edges, and evidence of more uniform lateral flow.

i. Less subsurface workhardening or damage as observed microscopically.

An Atomic Energy Commission installation is currently using ultrasonic tool posts and boring bars for machining certain difficult-to-machine ceramics; reportedly the major objective of this work--improved surface finish--is being reproducibly achieved.

Thus production application of ultrasonic boring and turning is imminent. Further efforts should involve establishing appropriate machining conditions for a wide range of materials, as well as developing heavy-duty ultrasonic systems for installation and use on turret lathes.

2. <u>Drilling</u> (Refs. 153-168, P92-P100)

Two types of ultrasonic drilling, both involving rotary tools, have received considerable attention within the last few years: drilling with a diamond-impregnated tool, for which standard commercial equipment is available, and twist drilling, which is in the prototype stage.

The rotary diamond-impregnated drill is an outgrowth of the ultrasonic abrasive slurry machining process that evolved to production use in the 1950's. In this case, the abrasive particles are added to the tool, and the tool is made to rotate to effect abrasion and material removal from the workpiece; the complexities of using a slurry are thus avoided. The rotary machine tool, which can be variously used for drilling, milling, and threading, can be installed on a standard drill press or milling machine. Its greatest usefulness is in machining nonmetallic materials such as ceramics, composites, and other hard, brittle materials. It is included here as a significant technique because of the increasing interest in boron-epoxy and other composites as aircraft materials.

Advantages of this type of drilling over non-ultrasonic processes for drilling such materials include:

a. Increased cutting rates (up to 100 percent increase).
b. Lower cutting forces on tool and workpiece.
c. Reduced tool loading.
d. Longer tool life (threefold increase).
e. Elimination of core seizure in core drilling.
f. Elimination of binding seizure in deep-hole drilling.
g. Increased drilling accuracy.
h. Less material tear-out and improved surface finish.

In view of its effectiveness in drilling composite materials, increasing production use should be made of this process. The largest size holes that can be effectively drilled with solid drills is about 3/8-inch diameter; with core drills, 1-1/2-inch holes in composites have reportedly been drilled at rates up to 2-1/2 inches per minute.

Ultrasonic twist drilling, for which prototype equipment is available, involves modification of a standard drill press to incorporate an axial ultrasonic system for twist drill activation. Its primary effectiveness is with metals, as demonstrated in work with aluminum, copper, steel, and titanium. Its advantages over standard twist drilling include:

a. Higher rates of material removal (up to fourfold and higher).
b. Reduced torque and thrust loads and elimination of chatter.
c. Less tool breakage and longer effective tool life.
d. Holes drilled to greater depth without tool retraction.
e. Improved chip clearance from the hole.
f. Cleaner hole breakout.
g. Improved dimensional tolerances.

This technique is available not only for ordinarily difficult-to-drill materials such as titanium, but also for soft gummy materials such as aluminum and copper, and requires only applications engineering for extension of its usefulness.

3. Milling and Broaching (Refs. 169-173)

Very little work has been done in applying ultrasonics to milling and broaching machines, but the few reports uncovered in the literature indicate effects similar to those obtained in other chip machining processes:

a. Reduced cutting force and power.
b. Increased depth of cut.
c. Increased rate of material removal.
d. Inhibited chatter.
e. Improved surface finish.

These effects have been demonstrated with materials such as aluminum, copper, steel, brass, titanium, and carbides.

Process development should be facilitated by the technology already evolved in other machining processes. Presently foreseeable applications are probably limited to relatively small-scale applications. The power available with existing ultrasonic equipment is not sufficient for a massive operation such as slab milling, for example, although future developments may well make it practical.

4. Thread Cutting (Refs. 174-180, P122)

Sufficient work has been carried out with ultrasonic thread cutting and tapping, using workpiece materials such as aluminum, copper, brass, steel, magnesium, and titanium, to indicate the potential of such processes in terms of:

a. Torque reduction (up to 93 percent specified).
b. Greatly improved ease of tool withdrawal and chip expulsion.
c. Accelerated cutting rates.
d. Elimination of workpiece tearing.
e. Improved thread quality and surface finish.

With the already accomplished development work in other ultrasonic machining operations, it appears that only moderate engineering development is required for production application, and that cost effectiveness can be evaluated on the basis of equipment purchase and operating costs versus product and process improvements.

5. Grinding (Refs. 181-192, P101-P106)

Work in ultrasonic grinding has progressed in three directions. One involves activation of the grinding wheel in any of several modes, another involves vibration of the workpiece as it is pressed against the wheel, and a third employs excitation of a coolant jet impinging against the wheel so that cavitation in the liquid rids the wheel of embedded metal particles.

Some of the reported results are contradictory, particularly with regard to effect on wear of the grinding wheel and on production rate. The most recent experimentation, however, shows beneficial effects on these parameters. In general, the improvements with ultrasonic activation of any of the three types are:

a. Substantially reduced wheel loading and longer times between redressings.

b. Increased wheel life, although some instances of more rapid wheel breakdown were observed.

c. Increased material removal rates (decreased rates were also noted).

d. Elimination or reduction in tool chatter.

e. Reduction in grinding temperatures by as much as several hundred degrees, with consequent elimination of warping, distortion, and other evidences of excessive heat.

f. Reduced residual stresses and stress cracking.

g. Improved surface finish and dimensional accuracy.

In several instances, ultrasonic grinding was used to sharpen steel and carbide cutting tools. In subsequent lathe turning (non-ultrasonic) of heat-resistant alloys, these tools exhibited up to 100 percent increase in tool life and also permitted increased cutting speeds.

Prototype equipment consisting of an ultrasonic spindle vibrating a special wheel and hub assembly has been installed and operated on internal, external, and surface grinders, and simulated production runs showed twofold to fivefold increase in material removal rates. It appears that production use of this process should be investigated in ter s of economic feasibility.

6. Finishing (Refs. 193-204, P107-P119)

Ultrasonic application is reported to produce beneficial effects in a variety of finishing process, including deburring, honing, lapping, polishing, and reaming, and production use is being made at least of ultrasonic deburring processes.

One such technique is an outgrowth of ultrasonic slurry machining, in which metal removal is effected by high-frequency hammering of the abrasive particles, induced by ultrasonic cavitation in the slurry, against the workpiece surfaces. For deburring, the workpieces are immersed in an ultrasonically activated liquid, which may be an etching solution, lubricant, or other liquid and which may contain abrasive or non-abrasive particles. Small, hard burrs and sharp edges are attacked first, and smooth surfaces are relatively unaffected. This technique is most effective for small precision parts where conventional tumbling and blasting can not be used. In one application, however, a large tank was assembled for ultrasonically deburring a 24-foot wing spar; output was tripled and manhours reduced by two-thirds.

In a variation of this immersion technique, a shaped cutting tool was used with an abrasive slurry to remove fine burrs. For deburring holes and slots, a small portable ultrasonic tool has been used without a liquid medium; because of the relatively low fatigue strength of the burr, it is rapidly loosened and removed.

Another finishing operation involved the use of ultrasonics in conjunction with electrochemical etching and chemical milling to remove nickel cladding from beryllium wire. The rate of material removal was increased, surface finish was smoother, and the finished wire showed higher strength and elongation in comparison with non-ultrasonically treated wire. In prototype production, 50,000 feet of wire was processed without replenishing the solutions.

Investigation of reaming with an ultrasonic torsional array mounted on a lathe demonstrated fourfold increase in speed, as well as improved surface finish and diametral precision.

Ultrasonic lapping and honing operations have likewise been carried out with increased rates of metal removal, reduced pressures, and improved surface finish. The ultrasonic activation had the effect of reducing glazing of the honing stones by fracture of the abrasive particles, thus continuously dressing the stone.

Production application of these finishing processes is in being or imminent, and their potentialities should be examined as a replacement for present laborious hand-finishing techniques.

C. Ultrasonic Metal Joining

The various ultrasonic processes included in the metal joining category (ultrasonic welding, diffusion bonding, wrenching, press fitting, soldering and brazing, and fusion welding) have little in common except they are all means for joining two or more metal components. Their basic mechanisms differ, ultrasonic equipment configurations are different, and different ultrasonic effects are involved. In all cases, however, the ultrasonic assist is observed to provide a stronger joint, more serviceable and more resistant to static and fatigue stresses.

Ultrasonic welding and diffusion bonding are solid-state metallurgical joining techniques wherein ultrasonic excitation ruptures surface films and promotes either interatomic diffusion across the interface or mechanical keying between the bare contiguous surfaces. Ultrasonic wrenching and press fitting are primarily friction reduction processes whereby closer mechanical fits are achieved with lower mechanical power requirements. Soldering and brazing involve cavitation in the molten solder or braze alloy to rupture surface films and permit wetting of the base metal. In fusion welding, ultrasonics acts on the weld metal in the molten state to retard or break up dendritic formations and produce refined grain structure along with the accompanying improved mechanical properties.

Of these processes, ultrasonic soldering and welding are accepted production techniques for a broad range of applications. Prototype ultrasonic wrenches have been developed and demonstrated on a pilot-plant basis. The other techniques require further engineering development to achieve equivalent status.

1. Ultrasonic Welding (Refs. 209-333, P129-P201)

This process, developed in the mid-1950's, has received more attention in the literature than any other ultrasonic metalworking process and is being used in production in a variety of applications.

Ultrasonic welding of metals is a solid-state process wherein the workpieces are clamped at moderate pressure between a welding tip or sonotrode and a supporting anvil, and vibratory energy is introduced in a direction parallel to the weld interface. The high-frequency alternating stresses rupture surface films, permitting nascent metal contact so that metallurgical bonding can occur without melting of the metal (which produces brittle cast structure) and without excessive deformation.

Commercial equipment is available covering power levels ranging from about 10 watts to 6 kilowatts and frequencies from 15 to 60 kilohertz. This equipment is of four basic types, for spot welding, ring welding (peripheral welds of various planform geometries), line welding, and continuous seam welding. A welder may be a completely contained unit or it may be a "kit" for installation on other processing equipment or in close-packed production lines.

Welds between a wide variety of similar and dissimilar metals, and also welds between metals and glass, ceramics, or other hard materials, can be effected using ultrasonic energy. The process is presently limited to sheet gauges below about 0.10 inch (there is no lower limit), and thin-to-thick metal weldments present no problem. Welding machine settings, which depend primarily on material hardness and thickness, are ultrasonic power, clamping force, and weld time; pulse time may be less than a second for spot, ring, or line welds, and rates up to several hundred feet per minute are possible for seam welds in thin foil material.

Some of the important advantages of ultrasonic welding over other joining techniques are:

a. Effective joining of both similar and dissimilar metal combinations, including high-strength, low-weight materials that may be otherwise joinable only with difficulty.

b. Joint strength approaching parent metal strength with no cast structure and no filler metal.

c. Capability of joining thin to thick metals, offering possibility of weight reduction.

d. Less critical surface preparation.

e. Capability of joining through coated, insulated, or adhesive-coated materials.

f. Thickness deformation of usually less than about 5 percent.

g. Power requirements lower than those of resistance welding.

h. Elimination of weight, time, and cost of surface preparation, forming rivet holes, and riveting.

i. Possibility of more efficient joint design because of reduced edge distance, spot spacing, etc.

j. Improved fatigue resistance.

k. Electrical conductivity and corrosion resistance values as high as those of the parent metals.

l. No degradation of joint strength at elevated temperatures.

m. Non-degradable joints in hermetic sealing by ring welding.

n. Amenability to fast automated production assembly.

Among the current production uses of the process are joining of components in the electronics industry, ring-weld encapsulation of sensitive

materials and devices, fabrication of nuclear fuel elements and bellows assemblies, splicing of aluminum foil in foil mills, aluminum honeycomb fabrication, assembly of heating and air conditioning ducts, and electrical connections of various types. Equipment and tooling developments are constantly being made in response to new applications and particularly as more stringent joining requirements are evolved for joints in the automotive, electrical, and other industries.

In the aircraft industry, acceptance of ultrasonic welding as a replacement for riveting and resistance welding in primary and secondary structures has been slow particularly because the process has never been qualified to military specification standards. Military specifications have been established for ultrasonic spot welding equipment,* and much strength data have been accumulated over the years of development and application, but a rigid process qualification program is required to provide a basis for aircraft industry acceptance.

2. Diffusion Bonding (Refs. 380-381)

Although very limited experimental data have been accumulated, ultrasonic activation during diffusion bonding promises significant reductions in bonding times (from hours to minutes), and thus has potential for becoming a practical means for assembling complex geometrical parts.

Russian work reported vacuum-sinter joining of copper washers in 30 seconds at 875°C with ultrasonic application where 1 hour at this temperature was required without ultrasonics; at 600°C, 6 minutes was required with and 8 hours without ultrasonics for the same assembly. American studies in diffusion bonding of beryllium showed a temperature reduction of 12-18 percent with a concomitant time reduction of 87-92 percent with a 25-second ultrasonic pulse during the early part of the bonding cycle.

To realize the advantages of such accelerated processing, development effort should be directed toward the mechanics of incorporating ultrasonic systems in conventional diffusion bonding apparatus and determining the interaction of ultrasonic and operating parameters for various materials and applications, particularly with aluminum and titanium alloys.

3. Wrenching (Refs. 382-389, P246-P248)

The potential of ultrasonically assisting the wrenching process has been demonstrated in the torque-tightening of flared tubing connections for aerospace applications, gear shaft assemblies, and bolt-nut assemblies, as well as in the disassembly of tightened fasteners that have become "frozen" in use. The process operates primarily by the reduction of friction between the mating thread surfaces, which is ordinarily recognized to consume as much as 90 percent of the torque required to tighten or loosen an assembly.

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* MIL-W-80187, dated Sept. 8, 1969, and MIL-W-80227, dated Aug. 25, 1971.

Experimental and prototype ultrasonic wrenches of both the manual and torque-stand types have been evolved, with activation of the wrench head in either the flexural or torsional mode. A prototype manual wrench for flared tubing connections was provided with multiple interchangeable wrench heads to accommodate fittings ranging from 1/8-inch to 1-inch diameter.

Experimentation has indicated that ultrasonic wrenching offers the following benefits:

a. Reduced torque to achieve a given preload on the fastener.

b. Increased relative rotation between components and increased tensile strain in the fastener without increasing applied torque.

c. Decreased residual torsional strain as a function of bolt preload.

d. Higher non-ultrasonic breakaway torque required to loosen ultrasonically tightened assemblies.

e. Less chance of vibrating loose under fatigue loading.

f. Higher sealing stresses on flared tubing connections, with lower incidence of leaking.

g. Possible reduction of variability in bolt tension values, although complete statistical validation has not been achieved.

h. Facilitated loosening of rusted or corroded fasteners, possibly obviating the need for drilling out the corroded member.

i. Possible elimination of the need for torque-multiplying devices, which are heavy, cumbersome, and awkward to use in confined spaces.

Although prototype wrenches have been designed and built for specific applications, these are not applicable to all torquing problems. Wrenches should be designed for example, for tightening or loosening fasteners in locations of poor accessibility. A lightweight, easily manipulated manual wrench for field maintenance use would have broad applicability.

4. Press Fitting (Refs. 390-395, P249-P250)

The assembly of components with close-tolerance or interference fits is facilitated with ultrasonic activation, usually in the axial mode, of one or both members. This phenomenon has been demonstrated in the telescoping assembly of concentric tubes, of a close-fitting ring on a mandrel, of tapered rods, pins, or shafts into sockets or bores, and of Hi-Lok type fasteners into sheet or plate material.

The effect is attributed primarily to friction reduction between the mating surfaces. Possibly the superposition of alternating stresses on the applied static stress also plays a role because of the relative motion thus imparted.

Such parts are often assembled by a static pressing or hammering action. In some applications, such as staking of bearings into forgings or plate material, the parts are differentially heated prior to assembly so that a tight fit is produced after temperature stabilization. Ultrasonically assisted staking or press fitting offers several advantages over such techniques:

a. Reduced static force requirement to achieve close-tolerance or interference fits.

b. Additional penetration of tapered fittings into bores.

c. Minimization of seizure, galling, scoring, or other damage to mating parts.

d. Elimination of differential heating of parts.

e. Reduced stress distortions in assembled parts.

f. Facilitated disassembly of press-fit parts.

The process has potential for a variety of assembly operations such as staking of bearings or bushings, insertion of straight or tapered pins into bores, installation of fastener fittings, assembly of gears onto shafts, installation of liner inserts, telescoping of concentric tubes, fabrication of bimetal tubing, etc.

Standard ultrasonic equipment is not available for such applications. Each type and geometry of assembly requires engineering development to determine (1) the most effective means of coupling vibratory energy into the part, (2) whether one or both components should be vibrated, and (3) the interaction of static force and ultrasonic power as a function of component material, time of ultrasonic application, and other variables. It appears that certain difficult assembly problems would justify the cost of such engineering development.

5. <u>Soldering and Brazing</u> (Refs. 334-379, P202-P245)

Ultrasonic soldering, tinning, and brazing was probably the first significant application of ultrasonics to metal processing. Conceived in the 1930's and developed in the 1940's, by the early 1950's it had become an effective production technique, and a variety of production equipment is available.

The process was initially developed for use with aluminum, which historically has been difficult to solder by the usual techniques because of the refractory oxide coating that forms on its surface instantaneously upon exposure to air and that is resistant to most ordinary soldering fluxes.

Ultrasonic soldering is accomplished without the use of flux. Vibratory energy transmitted through molten solder on the aluminum surface generates violent cavitation in the solder which hammers at high frequency against the oxide film and effects its removal, exposing bare aluminum which is then readily wetted by the solder. The process has been extended for use with other metals and to the higher temperatures required for brazing operations.

Two basic types of soldering equipment are available: self-contained manual soldering irons, similar in appearance to ordinary soldering irons but containing a transducer for excitation of the tip; and ultrasonically activated soldering baths, containing molten solder into which the parts to be soldered or tinned are immersed. The soldering irons may contain integral tip heaters for melting the solder or may be used with external heat sources. Soldering baths must be heated to maintain the solder in a molten state. Vibratory energy may be transmitted through walls of the bath, or an ultrasonically activated soldering iron may be immersed in the solder in close proximity to the part to be tinned or joined. With either type of equipment, parts may be tinned and later "sweated" together or joined by ordinary soldering techniques.

Recognized advantages of soldering and brazing are:

a. Elimination of fluxing which permits greater ease of soldering.

b. Elimination of meticulous pre-solder and post-solder cleaning operations.

c. Greater corrosion resistance of soldered joint because there is no chance of flux entrapment.

d. Improved wetting by the solder inside sharp corners and small crevices.

e. Effective joining of both similar and dissimilar metals, including ordinarily difficult-to-join materials such as aluminum, uranium, germanium, and Kovar, as well as metals to nonmetals.

f. Stronger and more uniform joints.

g. Solder selection on basis of end use rather than wettability.

h. Possibility of tinning and soldering enamel-coated wires without pre-stripping, since the cavitating solder ruptures such coating materials. Other insulation coatings are effectively removed with higher temperature brazing operations.

i. Adaptability of the process to high-quality, high-production-rate processes.

Typical production applications include: pretinning of wire leads and other components for the electronics industry, soldering tubing and fittings for refrigerator and air conditioning systems, assembling antenna structures, joining bare or insulated electrical wires, joining and repairing aluminum die castings, and sealing of pressure vessels, cans, and the like. New and different applications generally require only the design of appropriate soldering tips and/or tooling.

6. Fusion Welding (Refs. 396-417, P251-P281)

Since the early 1940's, ultrasonic application to fusion welding processes, including both resistance spot welding and arc or inert-gas welding, has been the subject of numerous investigations and patent conceptions, and beneficial effects have been reported. Apparently none of the techniques has achieved production status, possibly because of difficulties associated with transmitting vibratory energy effectively into the molten weld metal; these difficulties are evident from the many approaches used.

In resistance welding, ultrasonic transducers have been installed in or on one or both electrodes, electrodes have been vibrated in or out of phase, vibratory energy has been introduced independently of the electrodes, and vibration has been applied before or after the weld cycle or during the squeeze, weld, or forge phase of the cycle. In arc or inert-gas welding, ultrasonic energy has been transmitted to the molten metal through (1) the welding rod, (2) an arc or gas torch, (3) a coupling liquid, (4) a wire introduced into the weld pool, or (5) the workpiece support structure or the workpiece itself.

Whatever the transmission medium, generally similar results have been obtained:

a. Refined grain structure and frequently elimination or breakup of dendrites.

b. Reduced porosity in the weld metal.

c. Reduced incidence of weld cracking.

d. Improved tensile, shear, and fatigue strength.

e. Improved corrosion resistance.

f. Elimination of necessity for post-weld annealing.

Various of the techniques have also been noted to disrupt surface films, improve surface wetting, reduce heat, energy, and/or pressure requirements, and reduce the size of the weld bead.

It is likely that further development of ultrasonically assisted resistance spot welding was diverted by the advent of ultrasonic solid-state welding. With other fusion welding processes, the improved weld structure obtained may not be justified in the light of the added equipment complexities. In either case, economic feasibility of these processes is questionable.

D. Present Status of Ultrasonic Metalworking

The present status of the various processes previously described is summarized in the chart of Table III.

As noted, six of these processes are in production use, at least for a limited range of applications: tube drawing (both plug drive and die drive systems), wire drawing (with submerged die), drilling with diamond-impregnated tools, finishing (deburring), welding (spot, ring, and continuous seam), and soldering and brazing. In some instances, new applications of certain of these processes may require further applications engineering and/or prototype equipment development.

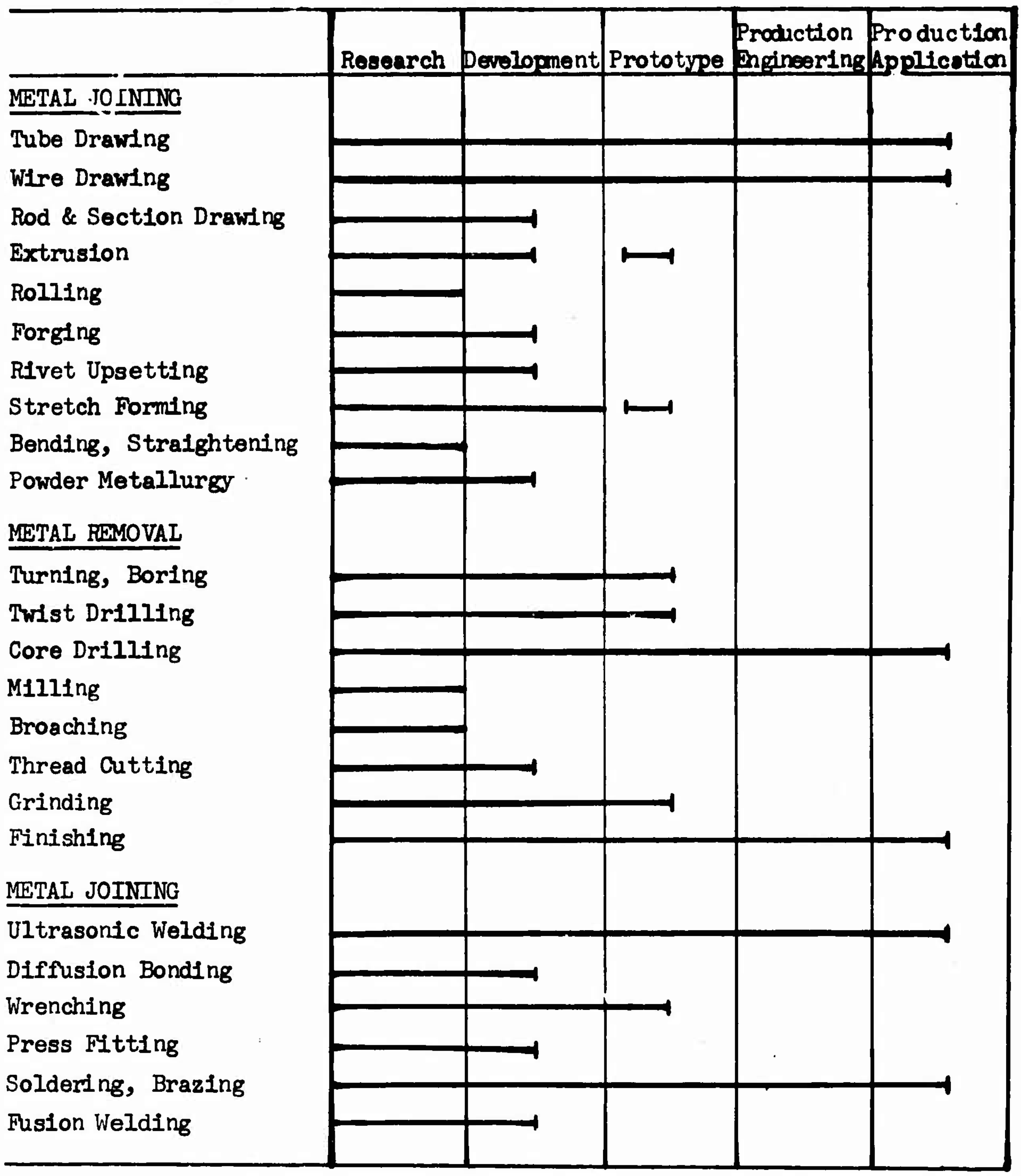
Prototype equipment has been evolved for lathe turning and boring, twist drilling, grinding, and wrenching, and for certain types of extrusion and stretch forming. Applications or production engineering is required for these processes to achieve production status.

All other processes require further development before production applicability can be established.

Figures 1-11 show typical production or prototype equipment for some of the more advanced processes.

Table III

PRESENT STATUS OF ULTRASONIC METALWORKING PROCESSES



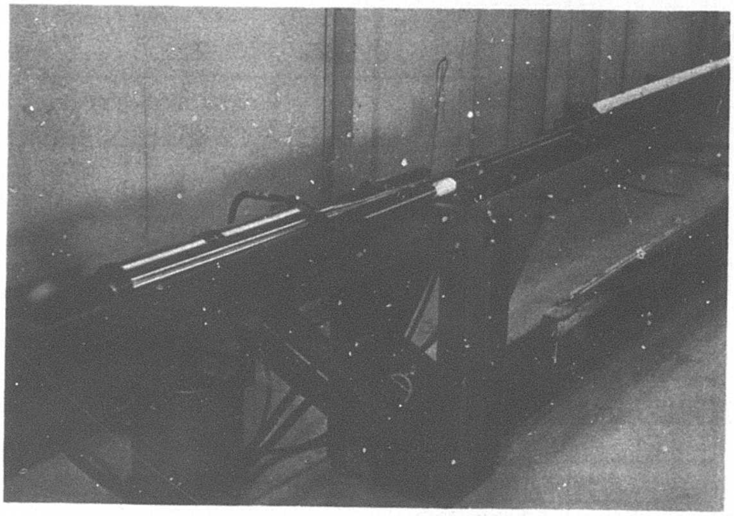


Figure 1

ULTRASONIC TUBE DRAWING
INSTALLATION
(Plug Drive System)

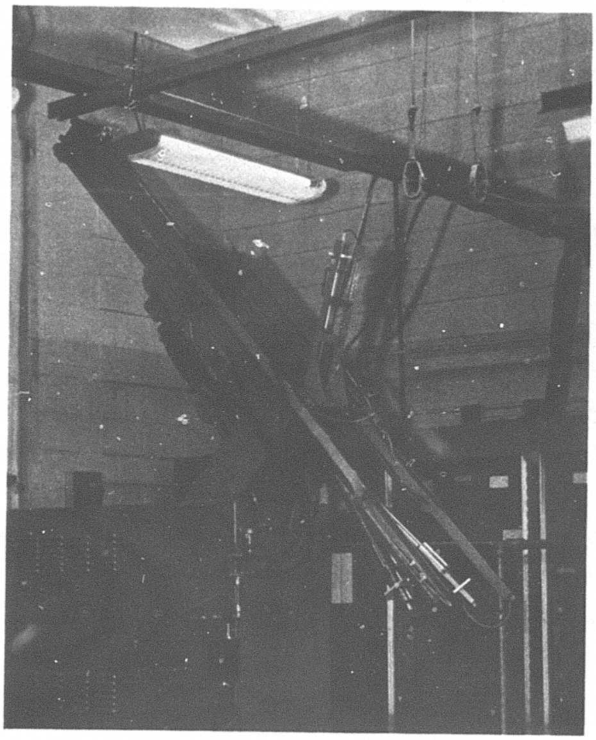


Figure 2

STANDARD 40-TON EXTRUSION
PRESS EQUIPPED FOR DIE
AND MANDREL ACTIVATION

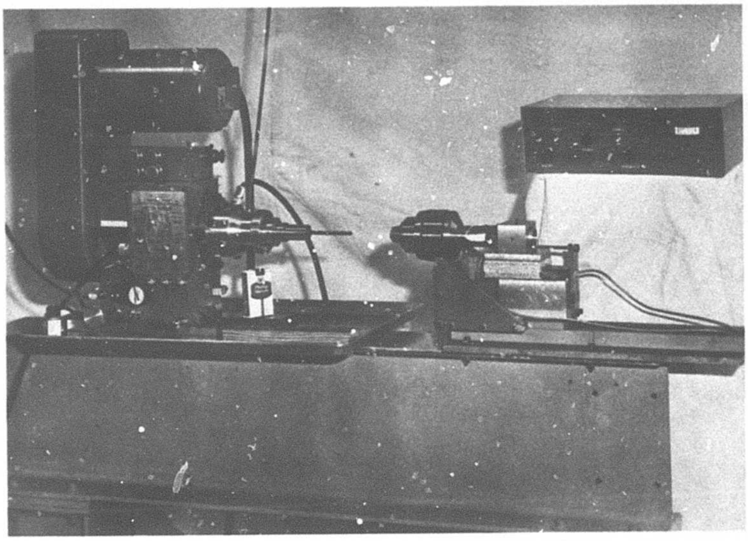


Figure 3

STANDARD TWIST DRILL HEAD INCORPORATING ULTRASONIC SYSTEM

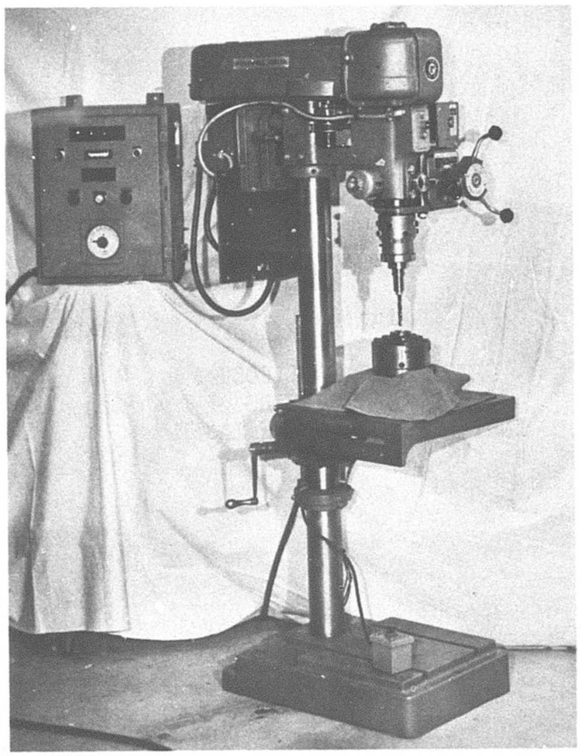


Figure 4

STANDARD TWIST DRILL HEAD INCORPORATING ULTRASONIC SYSTEM

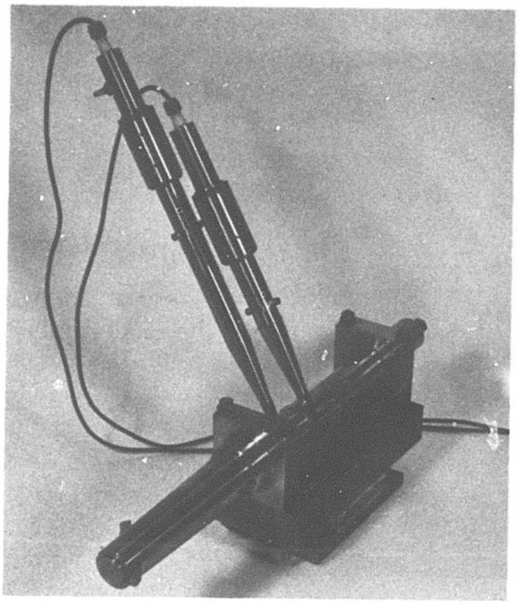


Figure 5

ULTRASONIC BORING SYSTEM
FOR ID MACHINING

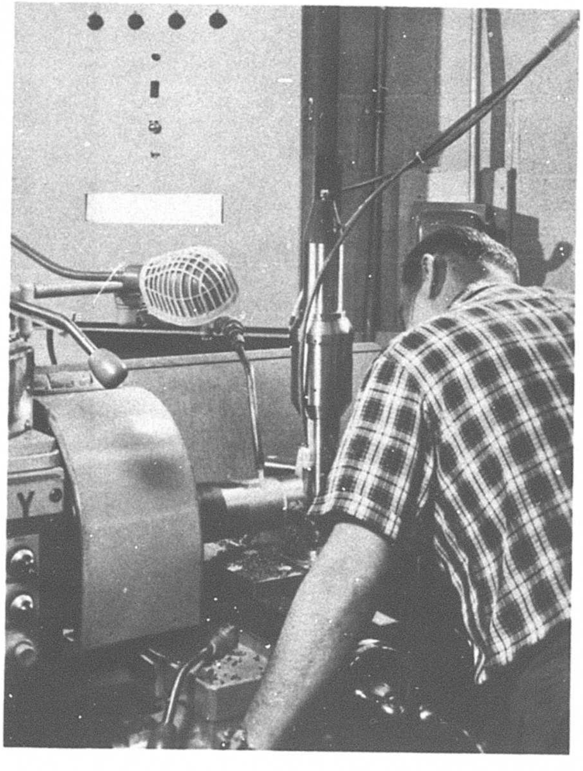
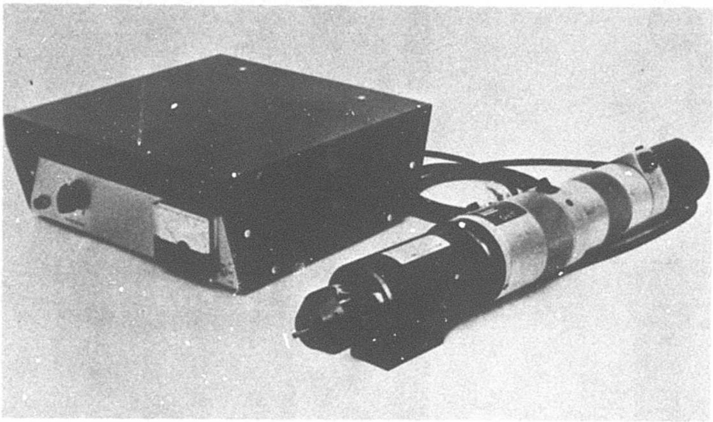
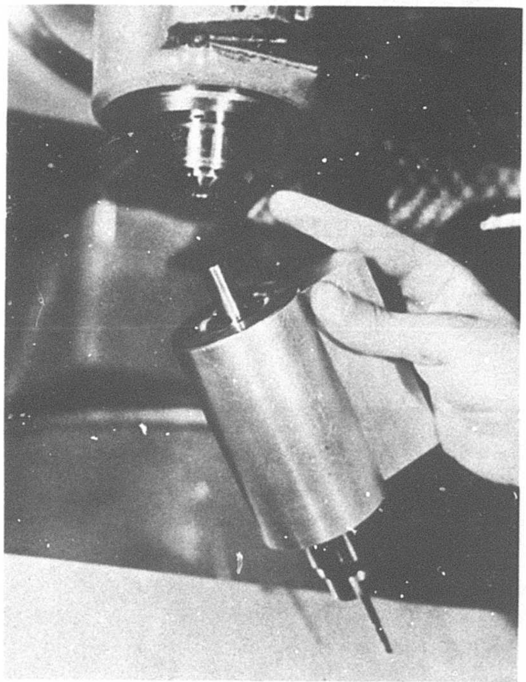


Figure 6

ULTRASONIC TOOL POST
FOR OD MACHINING
INSTALLED ON ENGINE LATHE



HIGH-SPEED ARO PORTABLE
AIR DRILL CONVERTED TO
ULTRASONIC DRILLING



ULTRASONIC DRILL ADAPTER
BEING INSTALLED IN
A BRIDGEPORT MILLER

Figure 7

ULTRASONIC CORE DRILLING UNITS
FOR COMPOSITE MATERIALS

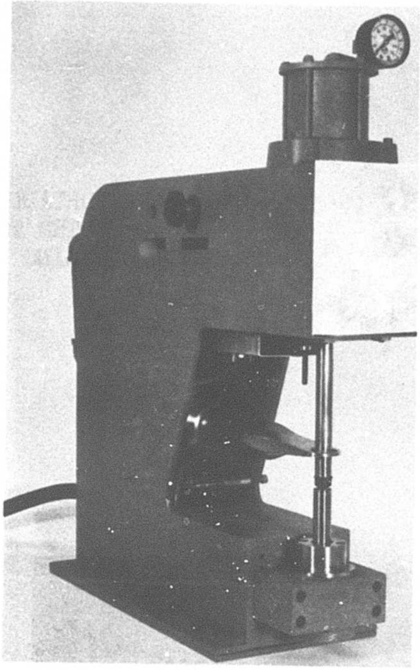


Figure 8

TYPICAL TABLE-MODEL
ULTRASONIC SPOT WELDER

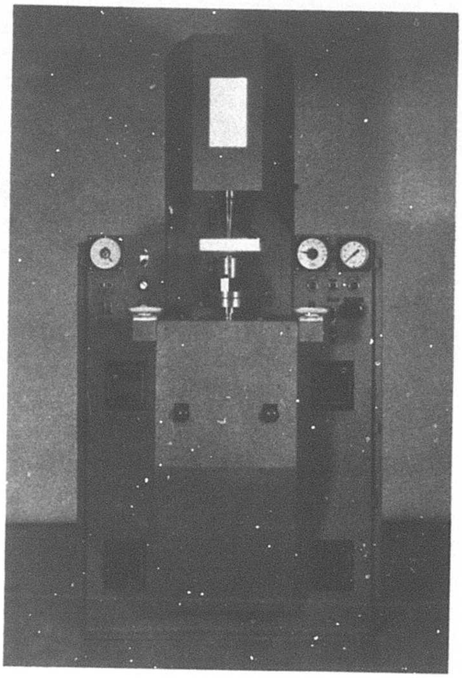


Figure 9

ULTRASONIC RING WELDER
WITH FREQUENCY CONVERTER
INCORPORATED IN CABINET

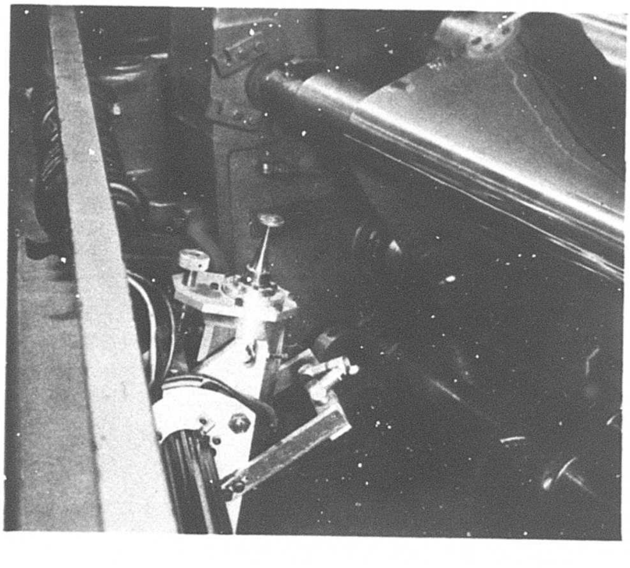
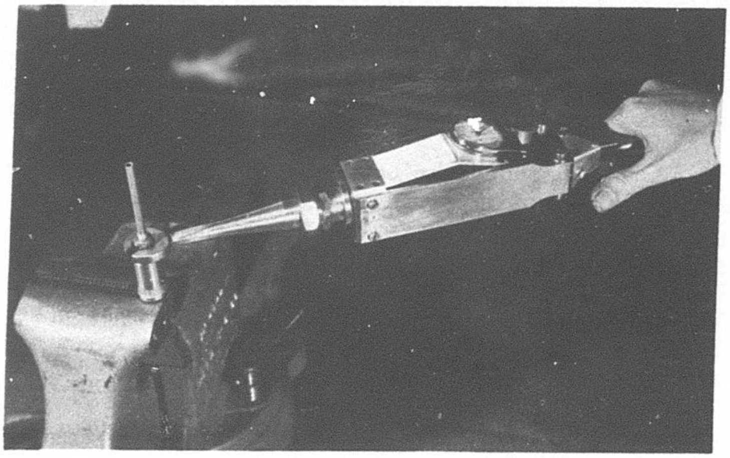


Figure 10

AUTOMATED CONTINUOUS-SEAM
WELDING (OF ALUMINUM FOIL)
SHOWING TRAVERSING TIP
ON RETRACTABLE GATE



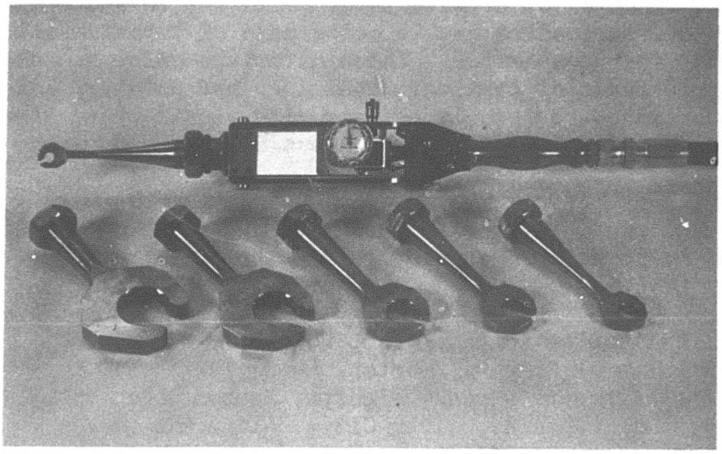


Figure 11

PROTOTYPE ULTRASONIC WRENCH
WITH INTERCHANGEABLE WRENCH HEADS

III. AIRCRAFT INDUSTRY SURVEY

Army helicopter and light aircraft manufacturers were surveyed in order to identify areas in the manufacture of such aircraft in which ultrasonic application may solve difficult fabrication problems, provide an improved product, and/or reduce processing time and costs.

Efforts in aircraft manufacturing are being directed toward reduced costs, decreased weight, and improved reliability and maintainability, particularly with regard to fatigue life. Helicopters in particular are subjected to intensive fatigue vibration manifested as low-frequency vibration from rotation of the main rotor, high-frequency vibration from the engine and tail rotor, and ground resonance. This behavior imposes severe demands on the materials and components of the structures. Failures may be merely inconvenient or they may be catastrophic.

Structural materials used in helicopters have heretofore been primarily aluminum and high-strength steel alloys; some magnesium is used, as well as honeycomb of aluminum or other materials. With the advanced aircraft now under development, increasing use is being made of titanium alloys and of boron or carbon fiber composites. These materials offer new challenges to the fabricator in terms of forming, machining, and joining, and frequently the more or less standard techniques used with aluminum and steel require modification to obtain the required high-quality components and assemblies.

To determine specific areas in which ultrasonic processing may offer solutions to such problems, visits were made and discussions held with representatives of the following manufacturers of Army helicopters and light aircraft:

1. Bell Helicopter Company, Fort Worth, Texas
2. Boeing Vertol Company, Morton, Pennsylvania
3. Cessna Aircraft Company, Wichita, Kansas
4. Hughes Helicopters, Culver City, California
5. Sikorsky Aircraft Division, United Aircraft Corporation, Stratford, Connecticut.

A concurrent visit to North American Rockwell, Los Angeles, California, revealed similar problems, although in connection with heavy aircraft manufacture. Information from this visit is included since it reinforces the evidence of need for improved processing.

The personnel interviewed were those closely associated with manufacturing processes, keenly aware of the limitations of existing techniques, and concerned with potential improvement: managers and directors of manufacturing engineering, tooling engineering, manufacturing research and development, and production development, as well as factory managers and project engineers.

In addition, extended discussions were held with Mr. George W. Townson,* who, with a broad background of experience in maintenance and repair of both military and civilian helicopters, provided insight into life cycles of components and field service, maintenance, and replacement requirements.

Varied initial reactions to the prospects of ultrasonic processing were encountered, ranging from skepticism to enthusiasm. The attitude of a few was that, although the benefits had been widely extolled, they had seen no concrete evidence of what could be accomplished. It was generally indicated, however, that ultrasonic technology for certain metalworking areas does not need to be sold; there was enthusiasm for the Army's interest in ultrasonic approaches to improved fabrication techniques; and there was urgent interest in obtaining equipment immediately to aid in problem solving and cost reduction.

Table IV shows the areas of expressed interest and the frequency of interest in each of the processes. The specifics of each problem area and the ultrasonic potential for solving the problem are discussed below. Some of these specific processes were selected for cost effectiveness studies; the supporting data are provided in Appendix A.

A. Metal Forming

Many of the problems associated with metal forming processes are related to the fact that all metals have limited plasticity and, as the limits of a metal's deformability are reached, the characteristics of the metal change markedly. The problems which then occur, including cracking, splitting, tearing, wrinkling, springback, and hardening, may be corrected by reworking or annealing the piece; alternatively the piece may have to be scrapped.

Ultrasonic assistance in these forming processes reduces or eliminates the problems mentioned by temporarily increasing the plasticity of the workpiece and/or by decreasing the friction between the tool and the workpiece, depending upon the process. Ancillary benefits, such as increased production rates and superior product quality, are described in the following sections as applicable.

1. Swaging

Several companies indicated problems in swaging the ends of control rod tubes. Present techniques are only partially effective, and up to 25 percent or more of the assemblies must be scrapped. A typical configuration consists of a 2024 aluminum alloy tube which is swaged down on both ends; the ends are tapped, and stainless steel tie rods are screwed in and locked with nuts.

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* Mr. Townson is Director of Maintenance, Copter, Inc., Philadelphia, Pa.; formerly Chief of Maintenance, Kellett Aircraft Corporation; Director of Training Aids, Boeing Vertol Division; Consultant for Pitcairn Industries; and Piasecki Helicopter Corporation.

Table IV

EXPRESSED INTEREST OF AIRCRAFT INDUSTRY
IN POTENTIAL OF ULTRASONIC METAL PROCESSING

	Company						
Process	A	B	C	D	E	F	G
METAL FORMING							
Swaging	x	x		x	x		
Tube Drawing							x
Section Drawing		x					x
Straightening		x					x
Tube Flaring			x				x
Tube Bending			x				
Rivet Upsetting		x	x				x
Dimpling			x				
Other Processes					x		
METAL REMOVAL							
Turning and Boring	x	x		x	x	x	x
Twist Drilling					x	x	x
Finishing					x		x
Milling		x		x		x	
Broaching	x						x
Core Drilling						x	
Thread Cutting		x					x
METAL JOINING							
Ultrasonic Welding	x	x		x	x		x
Diffusion Bonding					x	x	
Wrenching		x		x		x	x
Press Fitting	x	x				x	x
Soldering and Brazing			x				x

Swage reduction of the tube ends often produces internal wrinkles or folds that may be a source of serious weakness and/or other difficulties in subsequent thread formation. Where heavy reductions (50-60 percent) are required, several intermediate anneals are not uncommon; final sizing is accomplished on a mandrel. In at least one instance, internal threads are subsequently upset-formed by a chipless tapping process, but because of internal flaws, precise thread contours accurately mating with the threads on the tie rod ends are not always achieved.

Ultrasonic application has potential for two stages of this operation because of its capability for reducing friction and facilitating metal flow. Applied during reducing of the tube ends in a process perhaps similar to that of drawing and ironing, the metal can be controlled to flow longitudinally rather than peripherally, thus minimizing formation of wrinkles and folds. One or more of the presently required intermediate anneals may also be eliminated, in line with experience in tube drawing and draw ironing. Ultrasonic swaging at this stage thus offers potential for reducing fabrication costs by reducing scrap loss and eliminating one or more processing steps.

An alternate method of effecting the required joining involves forming the internal threads directly onto the threaded tie rod ends. This would eliminate the need for upset-forming the threads, a process of uncertain effectiveness. Ultrasonic activation of the swaging tool can cause the metal of the control tube to flow into the thread grooves on the tie rod end, effecting complete thread fill.

A modified version of this concept, proposed in Appendix A, involves providing the tie rod end shank with radial and axial grooves rather than threads, ultrasonically friction fitting the shank into the swaged tube end, and ultrasonically swaging the tube material into the grooves. The cost reduction study in Appendix A indicates that this modified technique will effect a 50 percent savings in the time now required to cut and swage the tube and lock the ends in place (from 28 minutes to 14 minutes), with concomitant cost savings.

2. Tube Drawing

Metal tubing in helicopters is used in engine mounts, drive shafting, and control systems. Generally such tubing is purchased to specifications by the prime manufacturers, and appears to present no problems. Interest was expressed, however, in the drawing of titanium tubing for hydraulic systems, and it was observed that stainless steel tubing will sometimes burst at the fittings, possibly because of flaws in the tubing.

Ultrasonic tube drawing equipment is immediately available and can be installed on conventional drawbenches or bull blocks with minor modifications. Its effectiveness in drawing steel and titanium alloy tubing, with concomitant product improvement, has been demonstrated on a production basis.

3. Section Drawing and Straightening

Problems are encountered in manufacturing the leading edge spar of a rotor blade, which is made of titanium alloy in a "D" section with a constant inside diameter and wall thickness varying from about 0.050 inch to 5/16 inch. Present fabrication involves hot rolling and drawing from rounds. The process requires about 18 minutes, and the product emerges so distorted that up to 4 hours of hand work may be required for straightening and conforming to required dimensional tolerances.

Ultrasonic cold drawing has been effectively used to produce titanium tubing up to about 0.5 inch OD by 0.030-inch wall thickness, with an area reduction of 23 percent and at drawing rates up to 100 feet per minute; conventional drawing was unsuccessful under these conditions. In addition, 11/16-inch-diameter 6Al-4V titanium alloy solid rods have been ultrasonically cold drawn to 7 percent area reduction at 100 feet per minute without the stick-slip that characterized non-ultrasonic drawing.

It therefore appears that ultrasonic application could alleviate problems in fabricating the rotor blade spar. This would probably involve substantial development effort, since hollow shapes of varying cross section and of the required size have not been previously drawn. Present tooling and fabrication techniques will need to be examined in greater detail to determine how ultrasonics might best be applied. There is, however, good possibility of reducing the drawing time required and of achieving closer dimensional accuracy so that subsequent hand operations would be substantially reduced.

The ultrasonic effect in straightening may also be effectively applied to assist in achieving the final geometry, further reducing the required finishing time. By setting up a series of progressive waves in the spar, introduced from one end and taken out at the opposite end, the yield strength of the material can be reduced and formability increased.

4. Tube Flaring

While not of major concern, flaring of aluminum alloy (5052, 6061, and 2024) tube fittings is sometimes accompanied by cracking and tearing of the metal, particularly where reverse bends are concerned. Tubing sizes of interest range up to about 2-1/2 inches diameter but are generally below about 3/4 inch.

Sound, crack-free flares and flanges have repeatedly been produced in aluminum alloys, as well as steel and other materials, with the use of an ultrasonic torsional system not unlike an ultrasonic ring welder except for the geometry of the flaring tool and the support tooling. Required static loads are substantially reduced, smoother surfaces without rippling are achieved, and closer flare tolerances are reproducibly obtained. This technique has been successfully used with tubing up to 1-1/4-inch diameter and wall thicknesses up to 0.035 inch, and equipment is available for processing up to 2-1/2-inch-diameter tubing. Development effort will be required to evolve tooling and techniques for reverse loop flares.

5. Stretch Forming

Several manufacturers expressed interest in improved forming techniques, for example, for titanium chafing strips for the rotor blade leading edge and for other rotor blade parts. Titanium alloy tends to crack in the area of the bend. Moreover, with processes such as cold forming or hydroforming, springback occurs, and excessive amounts of manual drop-hammer and rebending work are required to achieve the desired geometry. One manufacturer has resorted to hot forming of the chafing strips, but heated dies for this process are expensive. If cold forming could be successfully accomplished, tooling and dies would be greatly simplified and costs substantially reduced.

Appropriate ultrasonic application during such forming operations could eliminate the requirement for heat, reduce required static loads, reduce springback, and facilitate forming without cracking. Development will be required to evolve effective means for introducing vibratory energy into a long object such as a chafing strip and to evaluate ultrasonic power requirements, and the economic feasibility of such an approach will need to be examined.

6. Tube Bending

Bending of 4340 steel tubing has been noted as a problem. The only known instance of applying ultrasonics to such an operation is contained in a U. S. patent specification (Ref. P62), which indicates beneficial effects in terms primarily of facilitated metal flow, lower bending force, and reduction in springback. This potential application will require development effort, but may be worthy of further consideration.

7. Riveting

Riveting is presently used for secondary structures such as attachment of ribs, stringers, stiffeners, reinforcement plates, and the like. Generally aluminum rivets are used and apparently present few problems, except that they are a costly fastening technique, particularly because of the time required for drilling and preparing the holes. Some problems were noted in upsetting titanium rivets, as well as Monel rivets used to attach weights on rotor tips.

One manufacturer was concerned with the noise level of hundreds of stationary and portable riveters operating in a single locale, and believed that the relatively quiet operation anticipated with ultrasonic riveters would be beneficial to the work environment.

Technical feasibility has been established for ultrasonic rivet upsetting. Shank expansion to fill the hole and formation of the head are accomplished more effectively and with lower applied forces than can be accomplished with existing riveters, so that the size of equipment required for a given type and size of rivet is reduced.

It should be noted that ultrasonic welding may provide a superior fastening method. A discussion of the benefits of substituting welding for riveting with a cost comparison of the two methods is contained in the "Riveting" section of Appendix A.

8. Dimpling

Dimpling of aircraft sheet material to accept countersunk rivets, screws, etc., generally used with aluminum sheet thicknesses in the range of 0.016 to 0.060 inch, apparently does not present a serious problem, although some difficulties with dimple tear-out, especially in the thinner sheets, have been encountered.

The efficacy of ultrasonic activation of a dimpling tool in the axial mode has been established for aluminum and titanium alloy sheet, although some of the systems used were force-sensitive and thus limited to the thinner sheets. Use of a torsional mode, as in flaring and flanging, in conjunction with a force-insensitive mount should effect superior results and permit dimpling in a range of sheet materials and thicknesses at lower loads than normally used and with less incidence of cracking and tearing. Equipment is available that can possibly be adapted to this process, but it will be necessary to evaluate the interaction of ultrasonic and operating variables for a given material.

9. Other Forming Processes

Among the aircraft manufacturers, little interest was expressed in exploring the ultrasonic assist capabilities to some of the basic metal forming processes, such as forging, extrusion, rolling, section or rod drawing, casting, or powder metallurgy processing. Generally, items produced by these processes are purchased from subcontractors, and specific problems in these areas are not a primary concern of the prime manufacturer.

There is concern, however, over the extensive processing required for some of these items after they are received, in order to meet rigid design standards. Generally forgings, extrusions, etc. are produced considerably oversized, and substantial machining is required. With forgings, for example, the final part may weigh 30 percent or less of the as-received forging. The balance is scrap. This represents a considerable loss in the case of titanium forgings, which may cost in the order of $10.00 per pound, while the scrap is worth 3 or 4 cents per pound.

At least one manufacturer suggested that the Army could profitably focus attention on the role that ultrasonics could play in improving these forming processes and the cost savings that could thus be effected.

While the application of ultrasonic energy to the production of large forgings is outside the capabilities of existing equipment and present plans, its use in the production of small forgings is a readily attainable goal. Typical in the workable size would be control system parts such as brackets, bell cranks, sockets, and rotor system yokes, where problems are presented because of inclusions, built-in stresses, and incipient cracks, any of which could lead to premature failure.

The demonstrated ultrasonic effects in achieving superior products with forgings, extrusions, and the like offers the possibility of producing such components more nearly to size, so that less secondary working is required, and scrap loss is significantly reduced. The superior quality could also reduce the number of rejects due to unacceptable flaws.

Ultrasonics also offers the possibility of using new materials and/or processes to produce critical parts such as gears or bearings, for example. Gear tooth failures are noted to present problems, and bearing races in service may undergo brinelling, spalling, and tearing. High-quality forgings produced with an ultrasonic assist could alleviate such difficulties and provide longer service life.

Ultrasonic powder metallurgy processing offers another approach to fabrication of such components. Tool makers and automotive companies are using powder metallurgy products (not ultrasonically produced) for many parts, but aircraft manufacturers are just beginning to recognize the potential for this type of fabrication. The increased densification, strength, and homogeneity obtained with ultrasonic application could be the avenue to achieving aircraft quality parts. The significant advantage here is that the part can be produced essentially to size, with little subsequent processing and with negligible loss of material as scrap. Thus substantial cost savings are inherent in the process.

B. Metal Removal

The three problems mentioned repeatedly in conjunction with metal removal processes in discussions with aircraft manufacturing personnel were residual stress, precipitating early product failure; control of cutting tool, resulting in inadequate surface quality, surface tearing, and metal buildup on the cutting tool; and excessive time and labor investments in manual operations.

The temporarily increased plasticity and reduced frictional forces associated with ultrasonic metalworking facilitate these removal processes by decreasing the power requirements and increasing the ease with which the cutting tool removes the metal. The problems mentioned are either reduced or eliminated, depending upon the process.

Additional benefits are also obtained, including increased metal removal rates, longer tool life, and increased machine and process capacity.

1. Turning and Boring

The potential of ultrasonically assisted turning and boring generated considerable interest among most of the manufacturers. The primary concerns with existing techniques appear to be surface finish and residual stresses, and substantial effort is being expended in cutter geometry, coolants, and other process variables to insure good surface finish and uniform stress distribution with no loss in part quality. For structural parts, hand finishing and polishing are frequently used to remove tool marks and other surface defects that could contribute to structural failure. Machining of titanium shafts and boring of gear hubs were problems specifically mentioned.

Ultrasonic machining has been noted to result in improved surface finish and less grain tear-out. Conventional machining usually produces a glossy surface, apparently resulting from tearing, material enfoldment, and burnishing, and microscopic examination shows a marked surface waviness. Ultrasonically machined surfaces have a mat finish with evidence of more complete shearing of the chips from the bulk material; surface waviness is essentially absent. The extent of the improvement needs further evaluation with a wider range of materials and machining conditions.

The possibility of relieving internal stresses and increasing fatigue strength with ultrasonic machining has not been intensively investigated, although there are indications that this effect could be significant. Ultrasonic stress relief has been demonstrated in ultrasonic bending and straightening operations, where springback is markedly reduced. In an investigation* of surface machining of titanium alloy by various techniques, including slab milling, chemical milling, grinding, electrical discharge machining, and ultrasonic slurry machining, the ultrasonically machined specimens showed the highest resistance to bending fatigue, and fatigue strength was increased by approximately 60 percent over that of the as-rolled material. Measurements with ultrasonically turned specimens should show similar stress relief, thus increasing the useful life of the part.

Other potential economic benefits of ultrasonic machining include significantly increased rates of material removal, longer tool life, and reduced tool forces, thus extending the capabilities of standard lathes.

Appendix A includes a cost analysis involving drilling, boring, and turning operations in the production of a sample helicopter part, both with and without ultrasonically assisted production methods. This analysis shows an estimated 69 percent reduction in production time and labor cost with the use of ultrasonics. In addition, the parts would have a lower reject and damaged part rate, further reducing production costs.

2. Drilling

Various drilling problems were encountered. In hard materials such as titanium alloys, deep-hole drilling (deeper than about four diameters) is difficult to accomplish; required tool forces are high, frequent tool withdrawals are necessary to clear the hole of chips, and there may be frequent tool breakage, possibly damaging the part. With many materials, tool breakout in conventional twist drilling leaves a jagged edge requiring subsequent hand finishing.

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* R. J. Rooney, "The Effect of Various Machining Processes on the Reversed Bending Fatigue Strength of A-110 AT Titanium Alloy Sheet," WADC Technical Report 57-310, Project 7360, Wright-Patterson Air Force Base, Ohio, Nov. 1957.

Such problems are alleviated with ultrasonic twist drilling, for which prototype equipment has been evolved and successfully demonstrated. In addition to increased rates of material removal, the process offers reduced tool torque and thrust loads, so that tool breakage is minimized; improved chip clearance from the hole and drilling to greater depths without tool retraction, substantially improved hole breakout, and longer effective tool life also characterize the process.

The drilling of composite materials and composites with laminates presents special problems which are being solved with ultrasonic core drilling using rotary diamond-impregnated tools. This process has shown increased drilling rates, reduced tool loads, minimized drill retraction for dislodging the core, improved surface finish, and reduced tool wear. Economics studies have shown substantially reduced costs per hole drilled.

Such core drilling is effective with laminated composites involving titanium alloy where the titanium sheet is less than about 1/8 inch thick. With thicker sheet, it has been necessary to resort to a stepped operation wherein a twist drill is used to penetrate the titanium sheet and a diamond-impregnated core drill is used for the composite material. A similar problem is involved in drilling through a dual-hardness metallic material such as is used for armor plate. Drilling tools and conditions that successfully penetrate the soft material are ineffective with the hard material, and vice versa.

For such drilling, concepts have been evolved for an ultrasonic array involving two concentric tools for alternate advance and retraction. In drilling laminated composites, for example, a carbide-tipped cutter could be used to drill through the titanium and a diamond cutter for the composite material. With an acoustical impedance-sensing device, the impedance change at the interface could signal the retraction of one tool and the advance of the other so that the operation through laminated materials would be essentially continuous, thus eliminating manual tool changes and manual indexing at each interface. A similar arrangement could be used for drilling through dual-hardness armor plate. Development effort is required to achieve such a dual-tip tool.

An analysis in Appendix A provides estimated cost figures on the following disadvantages of conventional twist drilling: excessive tool wear and tool breakage; inspection and removal of broken drill bits; reworking or scrapped parts necessitated by deformation of hollow tube workpieces, and oversized holes caused by "orbiting" drill bits. These disadvantages can be alleviated or eliminated by ultrasonically assisting the drilling process. The analysis indicates that $64.80 per ship can be saved on control rod assemblies alone.

3. Broaching

One company indicated broaching to be a serious problem, for example, in the production of square and round fluted holes ranging from 1 inch to 4 inches in size in 4340 and 17-4 PH steels. Carbide cutters are used, and to be successfully broached, the material must have tensile strength in the

range of 160,000-180,000 psi. With softer materials, the process is unsuccessful. Troublesome aspects include metal buildup on the broach teeth, generation of surface tears and other defects in the workpiece, strength limitations, and residual stresses induced in the parts, which can range from 30,000 to 50,000 psi and can lead to serious corrosion and fatigue problems. The high cost of the broaching tool is also a significant factor.

The success achieved with ultrasonic application in other metal removal processes indicates that effective activation of a broaching tool is capable of achievement and could produce a significantly improved product, although development (based on existing ultrasonic machining technology) would be required for this application.

4. Milling

Milling is extensively used by the aircraft manufacturers to shape castings and forgings, and, as previously noted, more than 70 percent of the material may be lost as chips. An increase in the metal removal rate with such workpieces would certainly offer time and cost savings.

Experimentation carried out with ultrasonically activated end milling and face milling tools has indicated accelerated material removal and reduced forces; in some instances, the depth of cut could be almost doubled. Moreover, satisfactory milling could be obtained with less rigid machines, according to some investigators. In the few instances in which ultrasonic milling has been attempted, vibration was generally introduced along the tool centerline.

Slab milling with ultrasonics has apparently not been explored, and, because of the size of the cutting tools, considerable extrapolation of the state of the art may be required. With appropriate development, the economic benefits could be substantial.

5. Thread Cutting

Thread cutting was observed to be a perennial problem, particularly with the higher strength alloys. The only specific example cited was threading of a titanium shaft, wherein current techniques generate unacceptable residual stresses. Improved surface finish would also be desirable.

As with other cutting processes, such problems can be alleviated with appropriate ultrasonic activation of the cutting tool. Experimental work has demonstrated improved surface finish and less tearing of the material, as well as reduced torque, increased processing rate, and improved chip expulsion. There is also good possibility of stress relief with ultrasonic processing. Development will be required to establish the best means for delivering vibratory energy to the tool/work interface, as well as appropriate processing parameters.

6. Finishing

Finishing of parts particularly after metal removal was observed to be one of the largest single-element costs in helicopter manufacture because it is primarily a hand operation. In some work areas, dozens of workers many be engaged solely in finishing operations such as deburring, honing, reaming, smoothing, eliminating tool marks, and the like. Particular problems have been observed with parts that require precision finish, such as hydraulic control pistons, the interior of transmission cases, and bores on the rotor hub.

As previously noted, ultrasonic application to other metal removal processes frequently results in improved surface finish, thus reducing the requirement for subsequent finishing operations.

In addition, several ultrasonic approaches may be used to facilitate certain types of finishing operations. Ultrasonic activation of a grinding wheel or honing tool has been proven effective. Also, a small, hand-operated ultrasonic deburring tool has been successfully used for such applications as removing the rough breakout left by a drilling tool. Since the burr generally has lower fatigue strength than the bulk material, it is readily removed with ultrasonic application. Effective use has also been made of an ultrasonically activated abrasive slurry bath in which parts are immersed for removal of extraneous material. Equipment for most of these operations is commercially available.

C. Metal Joining

The major problems associated with metal joining processes involve preparation of the workpieces to be joined (cleaning, drilling, alignment), process requirements such as high and low temperature processing locales, and side effects of the joining methods (uneven resultant stresses, undesirable workpiece deformation, lack of process precision).

The different ultrasonic metal joining methods described below resolve these difficulties in markedly different ways, but each avoids most of the problems associated with conventional joining methods.

1. Ultrasonic Welding

A number of problems amenable to solution by ultrasonic welding were uncovered, and this process offers one of the most fertile sources for improvement in joining technology because of the immediate availability of a variety of types and sizes of production ultrasonic welding equipment.

a. Secondary Structures

One major area is the use of ultrasonic spot welding to replace resistance welding, riveting, or adhesive bonding for secondary structures such as the attachment of skin to skin, stringers, stiffeners, and honeycomb, for attachment of access ports, cowling, for door fabrication, and the like.

Resistance welding is limited to maximum sheet thickness ratios of about 3:1; it is not reliably reproducible, and machine settings require periodic (often daily) adjustment and requalification; and joint efficiencies are lower than desirable because of the brittle cast of the weld nugget. Indications are that resistance welding is being phased out in favor of other joining techniques.

In ultrasonic welding, only three machine settings (power, time, and clamping force) require adjustment for different workpieces, and once the settings are established for a given application, no further adjustments are required to achieve reproducible results. Furthermore, the welds are solid-state bonds with no cast nugget or intermetallics in dissimilar joints that are susceptible to accelerated fatigue. The materials and sheet gages of interest, generally aluminum alloys less than 0.100 inch thick, are within the capabilities of existing equipment. No maximum thickness ratios are applicable in ultrasonic welding.

Riveting as a means for joining secondary structures is often used without enthusiasm because of the high cost of drilling the holes, and it has been observed that the difference between winning and losing a bid on aircraft structures is dependent upon cutting down on the number of rivets. Some aircraft companies are utilizing commercial DRIVMATIC machines,* which drill and countersink the hole, insert the rivet, upset the rivet head, and may even shave the head to produce a flush surface, in successive automatic operations. These machines are claimed to have the capability of installing 18 rivets per minute. The experience of one manufacturer, however, indicates a maximum rate of 9.2 rivets per minute for the most accomplished mechanic and 7 rivets per minute for the average mechanic. Moreover, most of the machines are massive and expensive. Ultrasonic welding of aluminum alloy sheets is accomplished generally in less than 1 second, so that substantially higher rates are obtainable.

The major drawback to immediate use of ultrasonic welding for secondary structures is the lack of specifications and qualification of the process for such applications. Until detailed specifications are developed, it cannot be used with confidence. Extensive data are required particularly on tensile-shear, cross tension, and fatigue strength in the various alloys and gauges of interest. Fatigue data would be particularly valuable; very limited experiments have indicated ultrasonic welds to be superior to resistance welds in fatigue strength. If this advantage can be statistically confirmed with a large number of specimens of various materials and sheet thicknesses, it will offer a significant advantage for helicopter structures.

b. Ultrasonic Weld Bonding

Another ultrasonic welding application, weld bonding, involves ultrasonically spot-bonding through the adhesive used to bond the rotor blade subassembly, honeycomb panels, or other members to ensure structural integrity

* Manufactured by Gemcor, Buffalo, New York.

and proper alignment during the assembly process. When the adhesive is oven-cured, the ultrasonic spot-bond location will be as strongly bonded as the rest of the assembly. Presently employed resistance weld-bonding techniques run the risk of overheating in the vicinity of the spot location, which precludes bond formation during oven curing, and the assembly may be rejected upon inspection.

Appendix A discusses this process in more detail in terms of the main rotor blade assembly.

Several manufacturers expressed the desire to bypass the labor-intensive, time-consuming processes involved in "lay-ups" of the pre-cured adhesive bond assemblies mentioned above. Ultrasonic weld bonding would enable far easier assembly handling prior to curing and finally provide more securely bonded units.

Even greater advantage would be obtained by using ultrasonic welding to replace adhesive bonding completely. Appendix A contains a detailed analysis of the use of these two joining methods in the fabrication of a helicopter door. The cost analysis included therein indicated substantial savings in time (119 minutes vs. 43.5 minutes for the fabrication of a single door) and costs with the substitution of ultrasonic welding.

c. Bolt Head Corrosion Protection

A major problem is presented in service use with corrosion of the sheets around exposed bolt and screw heads, even though such areas are coated with corrosion-resistant paint. Fatigue stresses may crack the paint and expose the metal to accelerated corrosion. One helicopter company, for example, has detailed inspection and maintenance procedures for the screws securing the inertia weights on the outboard end of the main rotor blades. Inspection must be made after the first 600 hours or 6 months of service, whichever occurs first, and thereafter after every 25 hours or 30 days. If there is any evidence of corrosion, blisters, or cracks in the paint, the paint is stripped, and the metal around the fastener head is inspected by dye penetrant techniques; if no defects are found, finishing treatment is again applied. Greater reliability of the corrosion protection means would significantly reduce maintenance and repair time and costs.

The technique of ultrasonically ring welding patches over bolt heads has been shown to provide reliable protection from corrosion and is worthy of introduction into production use. Engineering for a production ultrasonic welder requiring access to only one side of an assembly should be undertaken to maximize utilization of this technique.

d. Miscellaneous Welding Applications

The phenomenon of fretting is constantly observed in the use of titanium for shafts and the like. Present techniques for preventing fretting involve the installation of a stainless steel sleeve on the shaft or a steel bushing in the ID bearing surface. The adhesive bonding now used is not

completely acceptable because of problems relating to cleaning, curing, etc. Ultrasonic welding of these assemblies could be accomplished in shorter time without the complexities of adhesives. No problems have been encountered in ultrasonically welding 0.010-inch stainless steel to a dissimilar metal such as titanium.

Another potential application concerns two helical gears which are joined at their mating flanges, currently by electron beam welding, to make a herringbone gear. The welding is expensive, and the heat generated by the process distorts the parts, causing variations in tooth alignment. Ultrasonic welding could accomplish this joint in a brief interval without heat distortion.

Ultrasonic ring welding also presents a means for bonding a vacuum-tight closure near the outboard end of the rotor "D" spar, which is now joined with adhesives.

On some helicopters, door shafts consisting of 2-1/4-inch OD tubing have brass weights bonded onto the exterior for balancing. Ultrasonic welding has potential for this application.

Although avionics is excluded from the scope of this investigation, the usefulness of ultrasonic welding in making electrical connections deserves mention, particularly for use in field maintenance and repair. Problems such as welding wires to harnesses in control panel assemblies have been reported. The capability for welding dissimilar metals such as aluminum and copper makes it a particularly valuable tool. A hand-held squeeze welder, for which design concepts have been evolved, appears to present especially useful potential for such applications.

2. Diffusion Bonding

Diffusion bonding has heretofore not been used to any great extent in helicopter and light aircraft manufacture, possibly because of the complexities and time involved in making such joints. This process, however, is now being investigated for aluminum and titanium joints for some of the newer aircraft. The high strengths that can be developed in diffusion bonded joints make this a candidate means for fabricating complex parts that are ordinarily machined from castings or forgings, permitting elimination of extensive machining and loss of material in chips. Integral stiffeners, T-joints, and the like are candidates for this processing. Investigations are currently being carried out under the auspices of Army Materials and Mechanics Research Center, Watertown, Massachusetts, to establish diffusion bonding techniques for such applications.

Although ultrasonically assisted diffusion bonding has not been extensively investigated, sufficient work has been carried out to demonstrate a dramatic decrease in time, and possibly also in temperature, in comparison to conventional diffusion bonding techniques. Bonding times have been reduced from hours to minutes, and temperatures concomitantly reduced by a few hundred degrees Centigrade. Further development will allow the manufacturers to use

this advanced fabrication technique to achieve the high-quality bonds required in aircraft structures.

3. Wrenching

Many torque fasteners are used in helicopter manufacture, especially in the transmission system, rotor assembly, and landing gear assembly. These may range in size from less than 1 inch to 16 inches or more in diameter. Small fasteners in the vicinity of 1 inch are used on gear and transmission cases. Larger fasteners of 4-6 inches are used to attach rotor fittings to spars. In some instances, the fasteners are sealed with epoxy on the first one or two threads to insure adequate fatigue resistance. Particularly troublesome are the large-diameter retainer nuts for thrust bearings, which are part of the main bearing assembly and in essence support the entire helicopter. In one instance, a 16-inch-diameter steel nut is installed on a titanium shaft, requiring torque loads up to 50,000 foot-pounds and higher. In this assembly, it is important that the nut does not gall or otherwise damage the titanium part (which may cost in the order of $70,000.00).

The significant advantage of ultrasonically assisted wrenching of such fasteners is the reduced torque required to achieve a given bolt tension and/or the increased bolt tension (up to 35 percent increase has been measured) achieved at a given torque level. Thus greater effectiveness can be achieved without increasing wrench capacity; with the reduced friction between mating threads, galling or other thread damage is minimized; and the higher bolt tensions provide added insurance against fatigue loosening of the fasteners.

An equally troublesome problem is the disassembly of torqued fasteners, particularly in field maintenance. Breakaway torque is usually about 50 percent higher than tightening torque, and the problem is aggravated for fasteners that are disassembled only infrequently, are rusted, or have been exposed to high in-service temperatures (as in the case of brakes) and have become "frozen." Disassembly is frequently impossible, and a bolt must be drilled out and replaced. Even fasteners that can be untorqued may not be reusable because of damage to head or threads.

Prototype ultrasonic wrenches have been developed for torquing and untorquing small-size fasteners. Development effort is required for fastener sizes in the range of 4 inches and larger.

The cost reduction study in Appendix A discusses the potential benefits of ultrasonic wrenching of aircraft fasteners, but without manhour and dollar figures. The stated advantages include:

a. Reduced time spent in recalibrating tools.

b. Less need for inspection as a result of increased accuracy and precision of torque values obtained.

c. Reduced rejection rate and need for retorquing.

d. The possibility of reduced work force resulting from reduced manual force requirements (up to 50 percent).

e. Higher output per worker as a result of reduction of manual fatigue.

f. The possibility of reduced tool size, facilitating work in the cramped spaces common in aircraft assembly.

4. Press Fitting

The assembly of parts with interference fits by press fitting or insertion fitting has presented serious difficulties. Typical examples are the assembly of parts in the rotor head, fitting of gears and bearings onto shafts, insertion of bearings into forged or machined parts, etc. Such assembly frequently utilizes a thermal differential between the two parts. For example, the part to be inserted may be frozen, as in liquid nitrogen, and the holder heated while the parts are forced together. Subsequent temperature stabilization may result in unpredictable or non-uniform stress distribution about the inserted part, with cracking or other damage to the holding member. Rejects of such assemblies are noted to be high.

Experimentation has indicated the feasibility of assembling components to interference fits at room temperature with ultrasonic activation of one or both members. The reduced frictional forces permit assembly with less susceptibility to damage or undesirable stress distributions. Ultrasonic equipment suitable for such assembly is available, although engineering is required for specific applications.

Appendix A includes an estimate in time and cost reduction required to produce a bearing-hub assembly typical of those used in helicopter manufacture. Assuming equivalence of product quality, ultrasonic press fitting can reduce labor costs by an estimated 35 percent and process time by an estimated 79 percent. Further cost reductions can be expected from:

a. Elimination of need for cooling bath and heating oven.
b. Increased productivity.
c. Decreased manpower requirements.
d. Decreased reworking and inspection costs.
e. Increased product reliability.

The Appendix also postulates that ultrasonics can, with the fabrication of interchangeable tooling such as holding fixtures and installing mandrels, increase the utilization of existing press fitting equipment.

5. Soldering and Brazing

A few soldering and brazing problems were identified but did not appear to be of first-order magnitude. Apparently heat exchangers and cooling systems are frequently assembled by such methods; generally these are purchased in the assembled state from subcontractors and, as long as they meet specifications, are not of particular concern to the prime manufacturers from the aspect of fabrication techniques.

One aircraft company mentioned a problem in brazing 4340 steel parts for landing gears. Brazing is carried out at 1800°F, followed by rapid quenching. Reject rate is high, perhaps because of the temperature differential during quenching. Ultrasonic application may alleviate this problem, but further investigation into the problem would be required.

Soldering is also used for electrical connections, and this sometimes presents problems in field service. The elimination of flux in ultrasonic soldering of aluminum junctions offers distinct advantages. However, even greater advantage would be obtained with the use of a hand-held ultrasonic welder for making such connections. Joints are stronger and more reliable for service use and are not degraded with elevated temperatures; this technique is equally effective in joining copper to copper, aluminum to aluminum, or aluminum to copper connections.

IV. SUMMARY AND CONCLUSIONS

The problem areas uncovered in the aircraft industry which appear to be amenable to solution with ultrasonic application were evaluated in terms of their potential for cost savings and the time required to achieve production use of the ultrasonic technology.

Those that offer good potential in cost savings and product improvement and that are either immediately available or can be evolved to production use within the short-term future (2-3 years) include:

1. Swaging of control rod tube ends.
2. Tube drawing.
3. Tube flaring.
4. Lathe turning and boring.
5. Twist drilling.
6. Core drilling of laminates.
7. Drilling of dual-hardness materials.
8. Broaching.
9. Ultrasonic welding of primary and secondary structures.
10. Ultrasonic welding for electrical systems.
11. Wrenching of small fasteners.
12. Press fitting.

An additional group of processes appear to offer good potential but will require further study of the problems and the technology presently used. These are candidates for long-range development:

1. Spar drawing.
2. Spar straightening.
3. Stretch forming, as of the rotor leading edge chafing strip.
4. Milling.
5. Thread cutting.
6. Diffusion bonding.
7. Wrenching of large fasteners.
8. Forging.
9. Extrusion.
10. Powder metallurgy processing.

A. Processes of Short-Range Applicability

Consideration was given to the time and cost required to achieve effective use of the more advanced ultrasonic techniques in the production manufacture of Army aircraft. Two of the processes--ultrasonic tube drawing and ultrasonic drilling of composites--are currently being used in production for similar type applications and can be applied without further development or engineering. Production equipment is available for ultrasonic welding, but this process will require qualification for aircraft purposes. For other processes, prototype equipment is available, but not necessarily of the type

or size required for aircraft industry use, and further development may be indicated. Technical feasibility of several processes has been demonstrated, but prototype development oriented to specific end uses will be required.

Table V provides estimates of the elapsed time and costs required for each process through the necessary stages: development through fabrication of prototype equipment; test and evaluation of production or prototype equipment for a specific application or range of applications; and tooling engineering to provide production-type equipment.

The production equipment costs provided in the last column are actual costs where available; otherwise these costs were estimated on the basis of the estimated acoustical horsepower probably required for the application and on the complexity of the equipment, based on experience with equipment of similar type. The price range provided in most instances represents the range of power outputs anticipated to be required for processing different materials, part sizes, etc. The equipment thus projected is for manual operation only.

The prices quoted are for ultrasonic equipment only and include the frequency converter, the transducer-coupling systems and associated accessories, and the necessary tooling. Ultrasonic welders are completely self-contained units, and this may be true of some of the other equipment such as ultrasonic wrenches or press-fitting devices. In other instances, the ultrasonic system will be capable of installation on standard metalworking equipment with some modification. Experience has indicated that such modification costs are usually about 10 percent of the ultrasonic equipment price if several machines are altered.

The production prices assume the manufacture of three or more identical units. If single units are desired, the costs may be somewhat higher. Time for fabrication and delivery of the equipment is usually in the order of 3 to 5 months.

The following comments are provided to explain and qualify the information provided in Table V:

1. Swaging

This projection is limited to the swaging of control rod tubes, both to reduce the diameter at the ends of the tubes and to swage the tube end onto the tie rod. Only one or two sizes and/or materials will be selected for development.

2. Tube Drawing

Available equipment is capable of handling tubing sizes up to about 2 inches OD by 0.20-inch wall thickness.

Table V

ESTIMATED TIME AND COST TO ACHIEVE PRODUCTION USE OF ULTRASONICS
(Qualifying comments are included in the accompanying text)

Process	Development Through Prototype		Test and Evaluation		Production (Tooling) Engineering		Production Equipment Cost
	Time	Cost	Time	Cost	Time	Cost	
SWAGING	8 mo	$ 75,000	9 mo	$ 100,000	--	--	$ 6,000 - 18,000
TUBE DRAWING	--	--	--	--	--	--	15,000 - 30,000
TUBE FLARING	8 mo	75,000	9 mo	100,000	--	--	4,000 - 15,000
TURNING	18 mo	200,000	12 mo	85,000	12 mo	$100,000	14,000 - 35,000
BORING	--	--	(Included in Turning)			--	30,000
TWIST DRILLING	6 mo	65,000	8 mo	75,000	6 mo	75,000	8,000 - 30,000
CORE DRILLING	--	--	--	--	--	--	10,000
DUAL HARDNESS DRILLING	14 mo	150,000	8 mo	100,000	8 mo	125,000	8,000 - 25,000
BROACHING	12 mo	100,000	5 mo	65,000	3 mo	50,000	5,000 - 20,000
ULTRASONIC WELDING - STRUCTURES	--	--	21 mo	2,000,000	3 mo	100,000	5,000 - 30,000
ULTRASONIC WELDING - ELECTRICAL	--	--	12 mo	75,000	--	--	2,500 - 10,000
WRENCHING	12 mo	125,000	6 mo	75,000	12 mo	150,000	1,000 - 10,000
PRESS FITTING	5 mo	50,000	5 mo	75,000	--	--	3,000 - 15,000

3. Tube Flaring

Tubing sizes up to about 1.0 or 1.5 inch diameter appear within the capabilities of existing technology. The process will involve rotation of either the transducer-coupling system or of the tube and its support tooling.

4. Lathe Turning

Prototype tool posts are available for installation on engine lathes only. The projected development is for turret lathe installations of 5 to 40 horsepower. A single installation will consist of one frequency converter and possibly four transducer-coupling systems. Test and evaluation data will be obtained on several materials.

5. Boring

Prototype ultrasonic boring bar designs for installation on engine lathes are available. It is contemplated that a 15-horsepower lathe will be thus equipped. Time and cost for test and evaluation are included in the figures for turning, since these processes are interrelated insofar as performance is concerned.

6. Twist Drilling

Existing laboratory-prototype equipment is for hole sizes up to about 1/2-inch diameter. The projected development is for ultrasonic drilling of holes of up to about 1-1/2-inch diameter in several materials. The ultrasonic systems will be capable of installation on more or less standard drill press equipment designs.

7. Core Drilling

Available equipment is capable of drilling holes of up to about 1/4-inch diameter in composites with a solid diamond-impregnated drill or up to about 1-1/2-inch diameter with a trepanning configuration.

8. Dual Hardness Drilling

This development is oriented toward a dual-tipped drill capable of drilling through laminates of composite materials with aluminum or titanium, laminates of metallic materials of differing hardnesses, and armor plate or the like consisting of a single material of dual hardness. Equipment is projected for hole sizes up to about 1/2-inch diameter.

9. Broaching

The development will involve hole sizes up to about 2-1/2 inches diameter.

10. Ultrasonic Welding of Structures

In order to use this process as a replacement for rivets or resistance welds in the assembly of primary or secondary structures, qualification for aircraft quality welding will be essential. The projected costs for Test and Evaluation include flight testing of ultrasonically welded structures.

11. Ultrasonic Welding for Electrical Systems

This will involve the welding of both wires and flat conductors. The required equipment is available, but this process also will require qualification testing for the selected applications.

12. Wrenching

Available prototype ultrasonic wrench designs are for tubing assemblies only. The projection here is for fasteners (cap screws, bolt and nut assemblies, etc.) in the size range of 1/4-inch to 1-1/2 inches diameter, and will involve both tightening and the loosening of corroded fasteners. Because of the many variables in the process (type of fastener, size, bolt length, and material), this program can be much larger or somewhat smaller, depending on the interest of the Army.

13. Press Fitting

This projection contemplates the press fitting of parts of up to about 2-1/2 inches diameter in various materials and material combinations.

Production unit cost savings that can be achieved with ultrasonic application to the above processes can at best only be estimated at this time, partly because of the unavailability in many cases of firm data on the costs of existing processes and partly because of the present development status of the ultrasonic process. The analyses in Appendix A indicate potential savings of 25 to 50 percent and higher for several of the processes. These data will need to be confirmed or modified with actual production experience.

Nevertheless, these processes appear to have good potential for significant cost reduction. As noted in the Introduction, cost savings are associated with several factors:

1. Increased processing rates.
2. Reduced power requirements.
3. Elimination of discrete processing steps.
4. Increased tool life, eliminating time and cost of tool changes.
5. Improved product quality, which leads to fewer rejects or reworks, longer component life, and reduced maintenance.

The demonstrated capabilities of ultrasonics in relation to each of these factors for each of the above processes are summarized in Table VI, generally only in qualitative terms. The implications for potential cost savings are certainly apparent.

Table VI-A

PRODUCTION SAVINGS POTENTIAL WITH ULTRASONIC PROCESSING
Processes of Short-Range Applicability

Process	Rate Acceleration	Energy Reduction	Elimination of Process Steps	Tool Life Increase	Quality Improvement
Swaging	Yes		Possible elimination of intermediate anneals		Smoother internal surfaces; improved fill of threads and grooves
Tube Drawing	To top mechanical capability of drawbench (up to a factor of 120)	Up to 78% reduced draw force	Reduced number of draws and between-draw anneals	Yes	Improved surface finish and dimensional control
Tube Flaring		Yes	Heating and annealing steps eliminated		Freedom from cracks and splits; smoother finish; closer tolerances
OD Turning and ID Boring	Yes	Up to 70% torque reduction	Deeper and therefore fewer cuts required	Yes	Improved surface finish due to reduced chatter; lower residual stress
Twist Drilling	By a factor of 6 or more	Reduced thrust and torque loads	Reduced need for tool withdrawal; minimized deburring of breakout hole	By a factor of 18 or more	Smoother breakout pattern; reduced residual stress; possibly improved ID surface finish
Core Drilling	By 30% or more	Yes	Reduced need for tool withdrawal	By a factor of 4 or more	Improved tolerance (to less than 0.001 inch); reduced material fracture
Broaching	Yes	Yes	Less finishing required	Yes	Improved finish; less tearing

Table VI-B

PRODUCTION SAVINGS POTENTIAL WITH ULTRASONIC PROCESSING
Processes of Short-Range Applicability

Process	Rate Acceleration	Energy Reduction	Elimination of Process Steps	Tool Life Increase	Quality Improvement
Welding	Bond produced in less than 1 second	Less power required than for resistance welding	Less critical surface preparation; no drilling required as for riveting		Improved strength and fatigue resistance
Wrenching	Accelerated removal of corroded fasteners	Up to 80% higher preload at given torque setting			Up to 27% higher breakaway torque; greater resistance to fatigue
Press Fitting		Reduced static force required; allows interference fits otherwise impossible	No heating and/or cooling of workpieces		Reduced stress distortion; minimized seizing, galling, scoring, etc.

B. Processes of Long-Range Applicability

The production potential of ultrasonic application for the second group of processes listed at the beginning of this section appears to be equally good, and the cost savings factors are similarly impressive, as summarized in Table VII.

These processes, however, are probably several years from production use. Most of them are still in the development stage, and relatively little is known about ultrasonic equipment size and configuration or process parameter interactions to envision end-use requirements. In some instances, as in spar drawing and straightening, further study needs to be made of the specifics of the problems and of present manufacturing techniques in order to determine how ultrasonics may best be applied. Consequently, it is virtually impossible at this time to make realistic estimates of the magnitude of effort required for development or to achieve production status.

They are presented here as candidates for further consideration and evaluation.

Table VII-A

PRODUCTION SAVINGS POTENTIAL WITH ULTRASONIC PROCESSING
Processes of Long-Range Applicability

Process	Rate Acceleration	Energy Reduction	Elimination of Process Steps	Tool Life Increase	Quality Improvement
Spar Drawing	Probably same advantages as for tube drawing (see Table VI)				
Spar Straightening			Subsequent hand work minimized		More permanent set; less springback; reduced residual stresses
Stretch Forming	Increased deformation with a given static load	Reduced static load; necessity for heated dies eliminated	Elimination of intermediate draw passes and anneals; reduced manual reworking; simplification of tools and dies		Elimination of cracks, splits, and ripples; reduction of springback
Milling	Yes	Yes	Less finishing required	Yes	Improved finish; less workhardening of material
Thread Cutting	Yes	Up to 93% torque reduction	Improved ease of tool withdrawal and chip expulsion		Tearing of workpiece eliminated; improved finish and thread quality
Diffusion Bonding	Time reduction from hours to minutes	Lower temperatures required			Reduced plastic deformation; possible recrystallization and grain refinement
Wrenching of Large Fasteners	Probably same advantages as for wrenching small fasteners (see Table VII)				

Table VII-B

PRODUCTION SAVINGS POTENTIAL WITH ULTRASONIC PROCESSING
Processes of Long-Range Applicability

Process	Rate Acceleration	Energy Reduction	Elimination of Process Steps	Tool Life Increase	Quality Improvement
Forging		Substantially reduced upsetting forces and temperatures	Less machining to final size; reduced scrap losses		Increased homogeneity and hardness; freedom from porosity and cracks; reduced residual stresses
Extrusion of Bulk Metals	Up to 300%	Force reduction by up to 50%	Higher extrusion ratios possible; less secondary working required; less scrap loss		Improved metal flow
Extrusion of Powdered Metals	Up to several hundredfold	Force reduction up to 90 percent; effective with mixes too stiff for conventional extrusion	Reduced plasticizer and water content; less secondary working required; easier handling before sintering		Increased density and strength; reduced porosity
Powder Metallurgy	Reduced time to achieve a given density	Reduced temperature and/or pressure to achieve a given density	Reduced binder or plasticizer or lubricant content in initial mix; less secondary working; greatly reduced scrap loss		Increased density and strength; greater dimensional stability and accuracy; improved surface finish

V. RECOMMENDATIONS

Recommendations for investigation and/or implementation of ultrasonic metalworking processes in support of AVSCOM requirements are presented below.

A. Present Production Processes

1. Drilling of composite materials with diamond-impregnated rotary ultrasonic tools should be utilized where applicable.

2. Ultrasonic tube drawing should be used for producing tubing that is now difficult to draw and/or for applications that require superior quality tubing.

B. Processes of Short-Range Applicability

3. Ultrasonic welding should be qualified for aircraft structural use, in association with an aircraft manufacturer.

4. Ultrasonic welding should be qualified as a means for joining wires and flat conductors in aircraft electrical systems.

5. Prototype ultrasonic equipment should be developed and evaluated for swaging control tube ends.

6. Prototype equipment for ultrasonic activation of tools on a turret lathe should be developed and evaluated in machining selected materials and geometries of interest.

7. The performance and cost effectiveness of an ultrasonic boring bar installed on an engine lathe should be evaluated.

8. Existing ultrasonic twist drill designs should be extrapolated to accommodate sizes up to about 1-1/2 inches and evaluated with several materials.

9. An ultrasonically activated dual retractable-tip drill should be developed and evaluated in drilling dual-hardness materials.

10. Ultrasonic wrenches for specific types and sizes of threaded aircraft fasteners should be evolved and evaluated both in tightening and in loosening corroded fasteners.

11. Ultrasonic equipment should be assembled and evaluated for press fitting parts of up to about 2-1/2 inches diameter.

12. An ultrasonic array for installation on standard tube flaring equipment should be designed, assembled, and evaluated.

13. The potential of ultrasonic broaching of holes up to about 2-1/2 inches diameter should be investigated with ultrasonic activation of the broach tool on standard equipment.

C. <u>Processes of Long-Range Applicability</u>

14. Investigation should be made of the possibility of facilitating drawing and straightening of rotor spars with ultrasonic activation.

15. Present techniques for forming rotor leading edge chafing strips should be reviewed to determine the possibilities of ultrasonic activation to alleviate present forming difficulties and reduce forming costs.

16. Consideration should be given to means for activating cutting tools in milling and thread cutting operations.

17. In view of the apparent substantial reduction in time required for diffusion bonding under ultrasonic influence, ultrasonic activation systems should be developed for diffusion bonding equipment and evaluated particularly for aluminum and titanium alloys.

18. Evaluation should be made of the ultrasonic requirements for facilitating the wrenching of large-size aircraft fasteners.

19. A survey should be made of Army aircraft subcontractors to identify other problem areas, particularly in primary material fabrication processes such as extrusion and forging, for an evaluation of potential ultrasonic application.

20. The possibilities of fabricating critical parts, such as gears, bearings, and small forgings by ultrasonic powder metallurgy processing should be examined and experimentation carried out on selected parts to determine the extent of product improvement obtainable.

APPENDIX A

COST REDUCTION STUDY

by

James D. Anderson

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APPENDIX A

COST REDUCTION STUDY

Several areas of metalworking, all directly related to metalworking in helicopter fabrication, are examined. In each area, certain manufacturing operations are analyzed to illustrate the manufacturing effectivity of the various processes used today. The feasibility of applying ultrasonic energy is discussed in each case, and a projected cost comparison is made, to serve as a basis for evaluating the practicability of ultrasonic application.

The metalworking areas encompassed by this study are:

A. Joining

 1. Ultrasonic welding vs. bonding
 2. Ultrasonic welding vs. riveting

B. Drilling

 1. Oleo-rod cross-pin drilling
 2. High-strength material drilling

C. Swaging

 1. Oleo-tube forming
 2. Control rod tube-end fitting assembly

D. Wrenching

 1. Transmission bolts
 2. Main rotor hub locknuts.

The major helicopter manufacturers were contacted and information solicited in each of the study-metalworking areas. Information was sought specifically in areas where the manufacturing effectivity was low, wherein either singly or in combination: (a) the manufacturing labor cost was considered very high, (b) productivity was low enough to be considered a problem, (c) the reject rate was excessive.

Each of these examples is examined to show the labor cost, the time necessary to manufacture, and the reject rate, insofar as such information was available. Following these analyses, the various processes are discussed individually to show how the application of ultrasonic energy could conceivably reduce cost, while improving quality and productivity.

In those discussions that involve labor dollars, the burdened manufacturing labor rate has, for the purpose of this report, been established at $15.00 per hour or $0.25 per minute.

Concluding the analyses in each of the study areas is a discussion of the ultrasonic equipment and tools that will be required and their estimated costs. Their availability for production ("Equipment Definition") is categorized as:

A. Technology and equipment immediately available.
B. Technology available, but equipment needs development.
C. Limited study needed before implementation.
D. Research and development needed.

I. JOINING

A. The Example

In the early production of helicopters by some manufacturers, the main cabin doors were riveted assemblies. Later, as tooling and methods were debugged and productivity increased, techniques were developed to adhesive-join the components by installing them in portable fixtures and subsequently placing them in an oven to cure the thermosetting adhesive. The problem with this method was (and in most cases still is) the time needed first to heat the loaded fixture and then, after the epoxy has been cured, to cool it down to a temperature where it can be handled safely.

To effect cost reduction and improve productivity, an integrally heated and cooled vacuum fixture was developed. Use of this tool reduced the time needed to make a bonded door from 289 minutes to 119 minutes.

B. The Condition

In most manufacturing assembly methods involving contoured parts, clamping pressure is required to varying degrees for correcting a contour mismatch between the various parts or for compressing the parts to the required proximity for bonding. The assembly must be heated to 275°-300°F and held at that temperature for 15 to 20 minutes to cure the adhesive. After curing, the oven (and contained parts) is cooled to a temperature that allows handling.

C. The Problem

The above-described method of fabricating doors does not present any specific part quality problem, but rather one of tooling and process. The inner and outer door parts must be formed to match nearly perfectly (within 0.005 inch) to permit reliable bonding. If not, the method of fixturing must clamp the parts and form one to the other to satisfy the optimum bond film thickness of 0.002 to 0.005 inch.

In this case, the parts are clamped by vacuum. The mismatch between the inner and outer doors is a combination of inner panel "springback" and variations from desired contours. The vacuum bagging brings the parts to within the desired bonding fit-up, but the required clamping pressure consistently flattens and distorts the inner panel, thereby reducing the area of the bond. Figures 12, 13, and 14 illustrate the method of layup and typical problems encountered.

D. The Solution

The door could be assembled by ultrasonic welding, with a substantial reduction in both labor dollars and elapsed time required. The welding fixture would be designed to permit welding the outer to the inner part (with the thin

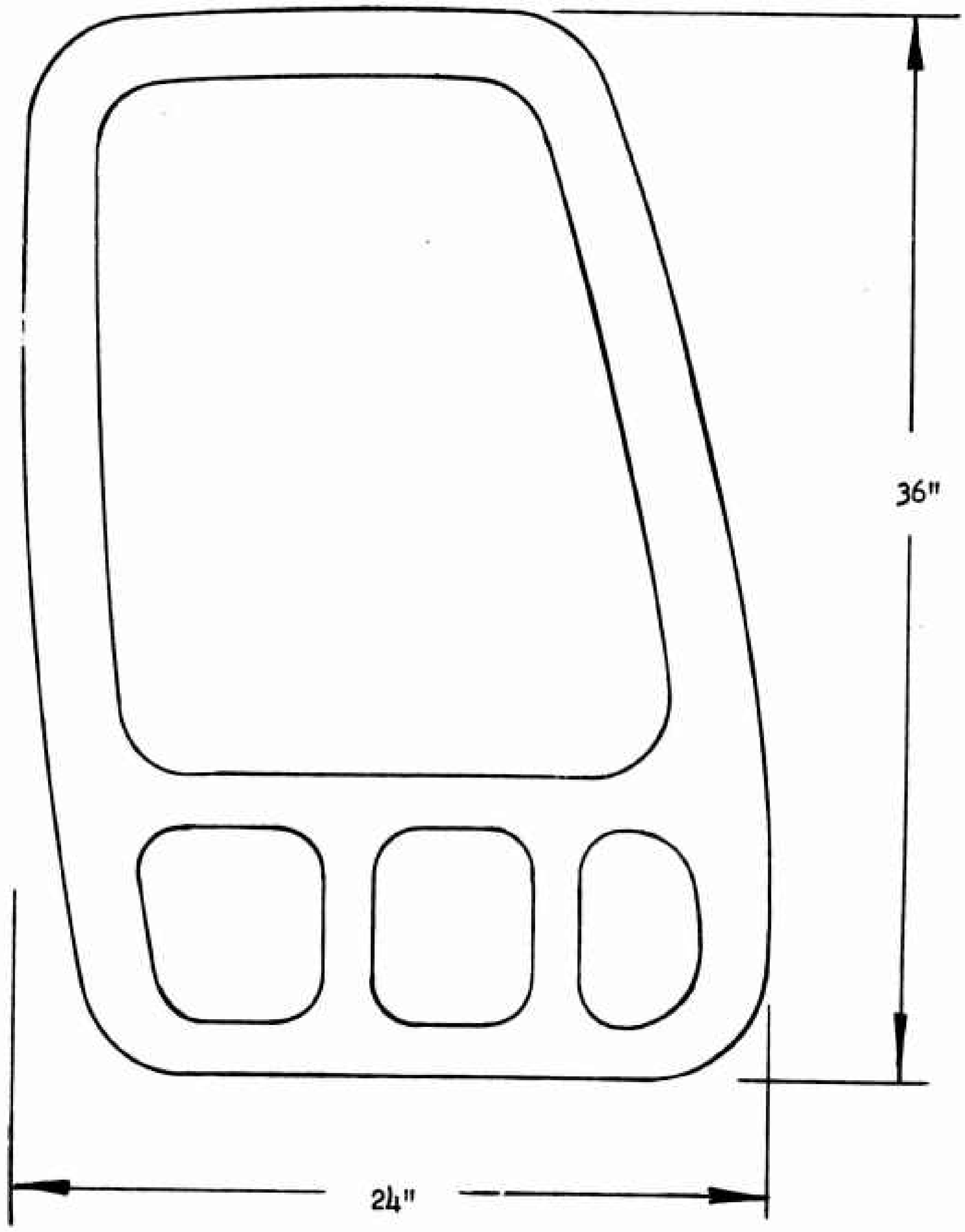
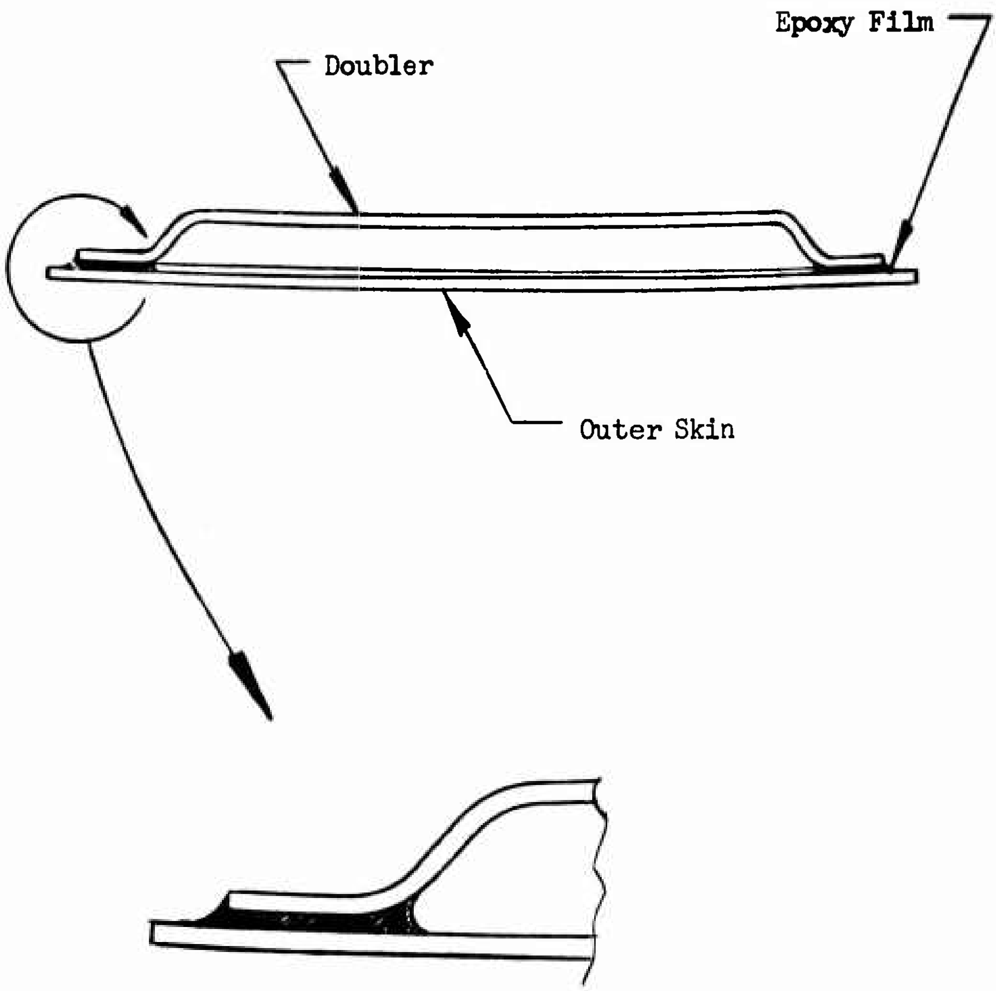


Figure 12

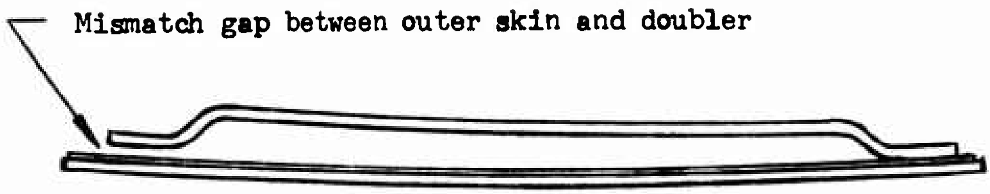
GENERAL SIZE AND SHAPE OF MAIN CABIN DOOR



After bonding, 0.002 to 0.005-inch bond thickness is desired.

Figure 13

METHOD OF ASSEMBLING DOOR



In order to close the gap, the vacuum must be increased to raise the clamping pressure.

The higher clamping pressure will buckle the doubler, causing metal-to-metal contact at A. The buckled areas exceed the possible bond film thickness, resulting in reduced bonded area (B).

Figure 14

TYPICAL PROBLEMS IN ADHESIVE BONDING OF DOORS

outer part adjacent to the ultrasonically activated welding tip, as shown in Figure 15). The ultrasonic welding process is accomplished in an extremely short time; 98 percent of the elapsed time is a combination of physically moving the part, together with the mechanical cycle of the welder. Only about 0.2 second is needed to make the actual weld.

E. Discussion

In order to make a projected comparison of the present process with ultrasonic welding, three welds per linear inch were established. These would be about 1/4 inch in diameter, similar in size and shape to an electrical resistance spotweld. With an estimated 320 linear inches of bonding area, approximately 960 welds would be required.

By ultrasonically welding the door, the vacuum bagging would no longer be required, nor would the layup of the adhesive. The inner and outer panels would be vacuum-fixtured, and the remaining parts would be located and clamped mechanically.

After fixturing, a series of tack-welds would be made to locate the parts and hold the assembly together; the door could then be removed from the fixture for completion of joining. Table VIII shows an analysis of the manufacturing labor costs of the present method versus projected costs of ultrasonically welding the cabin doors.

It should be pointed out that conventional spotwelding is not always suitable in aircraft, particularly rotary-wing aircraft, due to the high probability of fatigue failure. Resistance welding is accomplished by both melting the metal in the weld zone and squeezing the parts together. As in most other welding processes, the material in the heated area undergoes grain enlargement, or "recasting," due to the rapid melting and cooling. Such changes in the crystalline structure reduce both the strength of the assembly and its life, because the weld-affected area will fail in fatigue. The helicopter, with all its cyclic vibrations, is especially susceptible to this type of failure.

Ultrasonic welding is not really welding as such, but is rather a form of diffusion bonding. There is no heat applied to the parts, just clamping pressure and lateral oscillation at high frequencies (usually 15-20 kilohertz). The joined area, on microscopic examination, shows true molecular diffusion, with a complete absence of an interstitial layer or evidence of recasting that could precipitate failure.

F. Equipment Definition

Ultrasonic welding technology and stationary equipment for this application are in existence (Category A). A portable welder would also be useful, and this will require some design and development (Category B). One stationary and one portable welder of 1000 to 2000 acoustical watts each would perform these and many similar operations. Each unit would cost up to $25,000 ($10 to $12 per acoustic watt), and delivery could be made in 4 to 6 months.

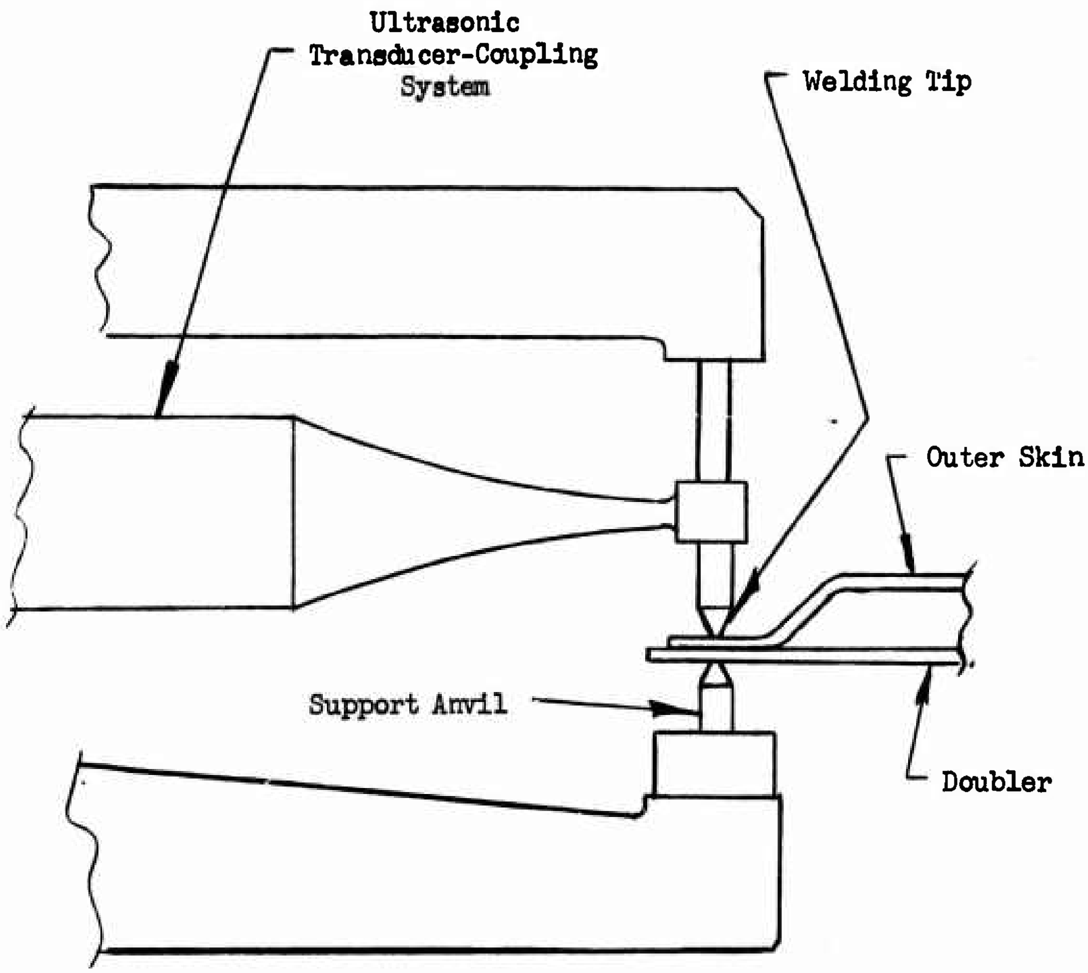


Figure 15

ULTRASONIC WELD TOOLING

Table VIII

DOOR FABRICATION COST ANALYSIS AND COMPARISON

Present Method

Operation	Time (minutes)	Cost
1. Fixture components with adhesive, apply vacuum	59	$14.75
2. Cure adhesive:		
Heat up	15	3.75
Cure at 285°F	35	8.75
Cool down	10	2.50
Totals	119	$29.75

Proposed Ultrasonic Welding Method

Operation	Time (minutes)	Cost
1. Fixture components	20	$ 5.00
2. Make 30 tack-welds	5	1.25
3. Remove assembly from fixture	3	0.75
4. Make 930 welds @ 60/min	15.5	3.89
Totals	43.5	$10.89

II. RIVETING

A. The Example

The helicopter structure and its method of manufacture are derived from and closely related to those used in aircraft manufacture. The ribs, stringers, stiffeners, and skins, predominantly aluminum, are joined together with rivets. One of the most widely used machines in airframe construction today is the Gemcor DRIVMATIC riveting machine. This unit, in an automatic cycle, drills, countersinks, rivets, and flush-machines the rivets.

B. The Condition

When the components of the airframe substructures become too large to be hand-held, fixturing is required; often special fixtures and handling devices are necessary. The riveting equipment necessarily must be large, and is frequently track-mounted to encompass the extended length and width of the parts.

C. The Problem

When the secondary or subassembly size increases beyond a size that is easily hand-held, the riveting machine size and cost increase dramatically. A machine to assemble light-gauge components in the 12-inch to 18-inch size range may cost $15,000. If the assembly size, as an example, is increased to 6 by 24 by 36 inches, hand-positioning is impossible and fixturing is necessary. If the metal thickness is increased to 0.125 inch, the riveting machine cost may be as much as $55,000 to $60,000.

If the assembly is one of the major airframe structures in the helicopter, the size and bulk of the part may require an extremely large machine and highly mobile tooling. The combined cost of these can easily approach $1,000,000.

The cyclic capability of the DRIVMATIC machine, which is listed at approximately 18 rivets per minute, has been established in production at a maximum of 7.2 rivets per minute under ideal conditions. This results in a labor cost of $0.035 per rivet, exclusive of rivet cost (see Table IX).

D. The Solution

Ultrasonic spotwelding can be used to perform the joining. The ultrasonic weld time would be considerably less than that needed to perform riveting, equipment cost would be reduced, and joint strength would be the equivalent or higher. Where possible, a stationary ultrasonic welding unit could be used. For applications where the assembly is too large or too heavy to be moved readily, a suspended mobile weld unit could be used.

Table IX

RIVETING VS. ULTRASONIC SPOT WELDING
COST ANALYSIS AND COMPARISON

Operation	Cost per Minute	Cost per Cycle	Feet per Minute	Cost per Foot
1. Possible DRIVMATIC cycle: 18 rivets per minute @ 2 per inch	$0.25	$0.014	0.75	$0.33
2. Actual DRIVMATIC production rate: 7.2 rivets per minute @ 2 per inch	0.25	0.035	0.30	0.83
3. Ultrasonic weld rate: 30 welds per minute @ 3 per inch	0.25	0.008	0.83	0.30

E. Discussion

Previous discussions have described the quality and reliability of the ultrasonic weld and its characteristics resembling a diffusion bond. In comparing ultrasonic welding to riveting, a 1/4-inch-diameter weld has been selected, as the welding styli will fit into virtually any space envelope that the riveter will.

Timewise, 98 percent of the weld cycle consists of moving from one weld location to another. Regardless of whether the machine is controlled and moved by a programmed sequential device or the part is positioned manually, the weld itself requires no more than about 0.2 second. It is estimated that hand-held assemblies could be ultrasonically welded at the rate of not less than 30 welds per minute, and possibly as high as 60 welds per minute; with fixtured assemblies and programmed welding equipment, the rate could be much higher.

Using a conservative 80 percent strength factor for the 1/4-inch-diameter ultrasonic weld versus the 1/8-inch-diameter rivet, the welded structure is three times as strong (three welds per inch versus two rivets). From Table IX, it can be deduced that the use of ultrasonic welding, when compared to conventional riveting, can effect a reduction of up to 30 percent in elapsed manufacturing time.

F. Equipment Definition

1. A stationary ultrasonic welding unit of about 1500 acoustic watts power would cost approximately $20,000 and would require about 4 months to fabricate. Some tooling development may be required (Category A).

2. A suspended manual unit of the same welding power would cost about $25,000-30,000 and would require about 6 months for fabrication. Limited design, equipment development, and technique refinement are required (Category B).

III. CONTROL ROD FABRICATION

A. Example I

The first control rod example presented here consists of a 2024 aluminum alloy tube swaged down on each end. In a special process known as chipless tapping, internal threads are upset-formed in each end; this is an extrusion process which makes no chips, as in conventional machining (see Figure 16). The formed threads are stronger and more fatigue-resistant than machined threads. Externally threaded tie-rod ends of 300 Series stainless steel are then screwed into position and locked with jamb-nuts.

1. The Condition

The tubes, in lengths from 1 foot to 15 feet, are swage-reduced from approximately 1-inch to 3/8-inch diameter, controlled to +0.002 inch, -0.000 inch. The tubes are then mounted in a lathe for the threading operation and rotated while the fluteless tap is fed into the work.

2. The Problem

The internal-upset threading operation has presented difficulties maintaining the desired standards. The reject rate is high, due mainly to sized pitch diameter of the threads, combined with eccentricity and torn threads. The time required to make the threads is also high (5 minutes per end to fixture, thread, check, and clean).

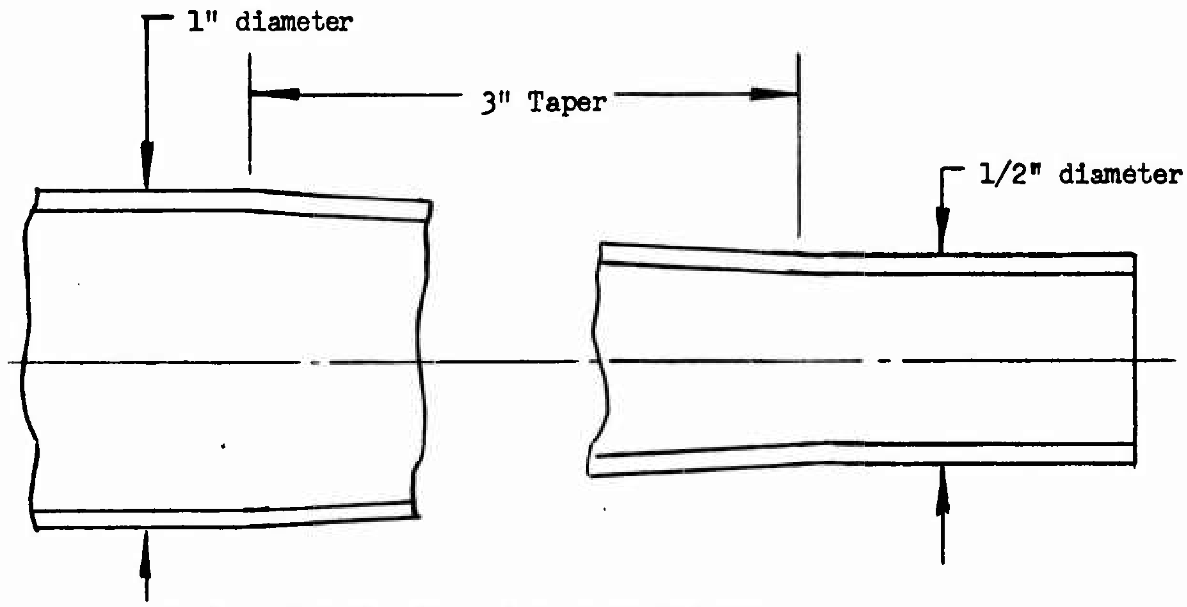
3. The Solution

The tube ends would continue to be necked-down to reduce the diameter. A straight-shanked tie-rod end would be interference-fitted in one end and an internally threaded bushing in the other end.

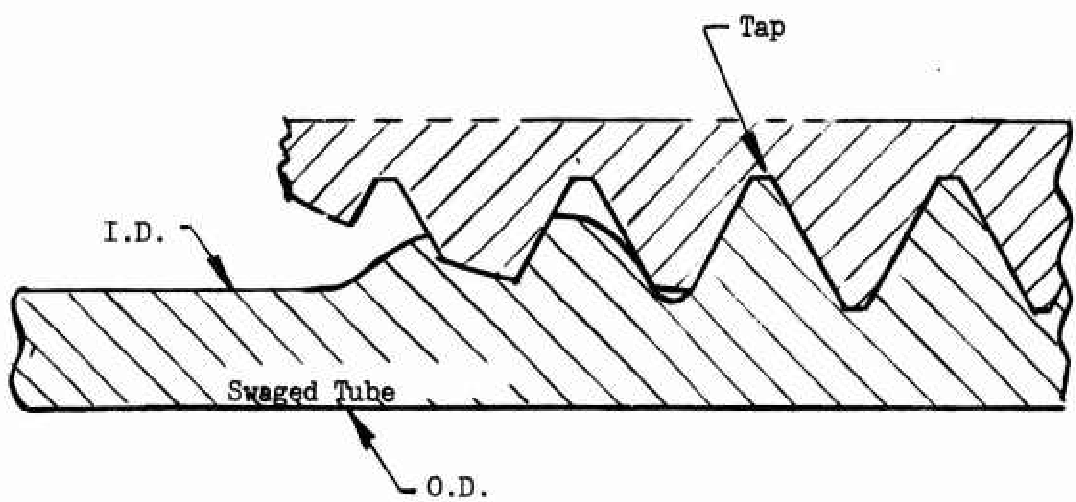
The tube fitting assembly would then be placed in an ultrasonic swaging tool, the die closed, and the tube swage-reduced on the fitting, as shown in Figure 17. This operation would ultrasonically extrude or upset the tubular material into provided diametral irregularities in the fitting, causing a permanent mechanical lock. The estimated swaging time needed to perform this operation would be 1 second per inch (2 seconds total).

4. Discussion

The chipless tapping of the swage-reduced control rod ends, as presently accomplished, appears to be very costly for two reasons. First, internal wrinkling of the tube wall during swaging causes many rejects, as the folds will later precipitate cracks, causing the tube to fail. Second, minor variations common to tools, parts, and equipment appear to combine to create excessive scrap due to oversize pitch diameters. The cost per part is not known, but it is obviously high.



Typical Existing Swaged Control Rod End



Enlarged Partial Section of Tube Wall, Showing Upsetting of the I.D. to Form the Threads

Figure 16

CONTROL ROD FABRICATION TECHNIQUES

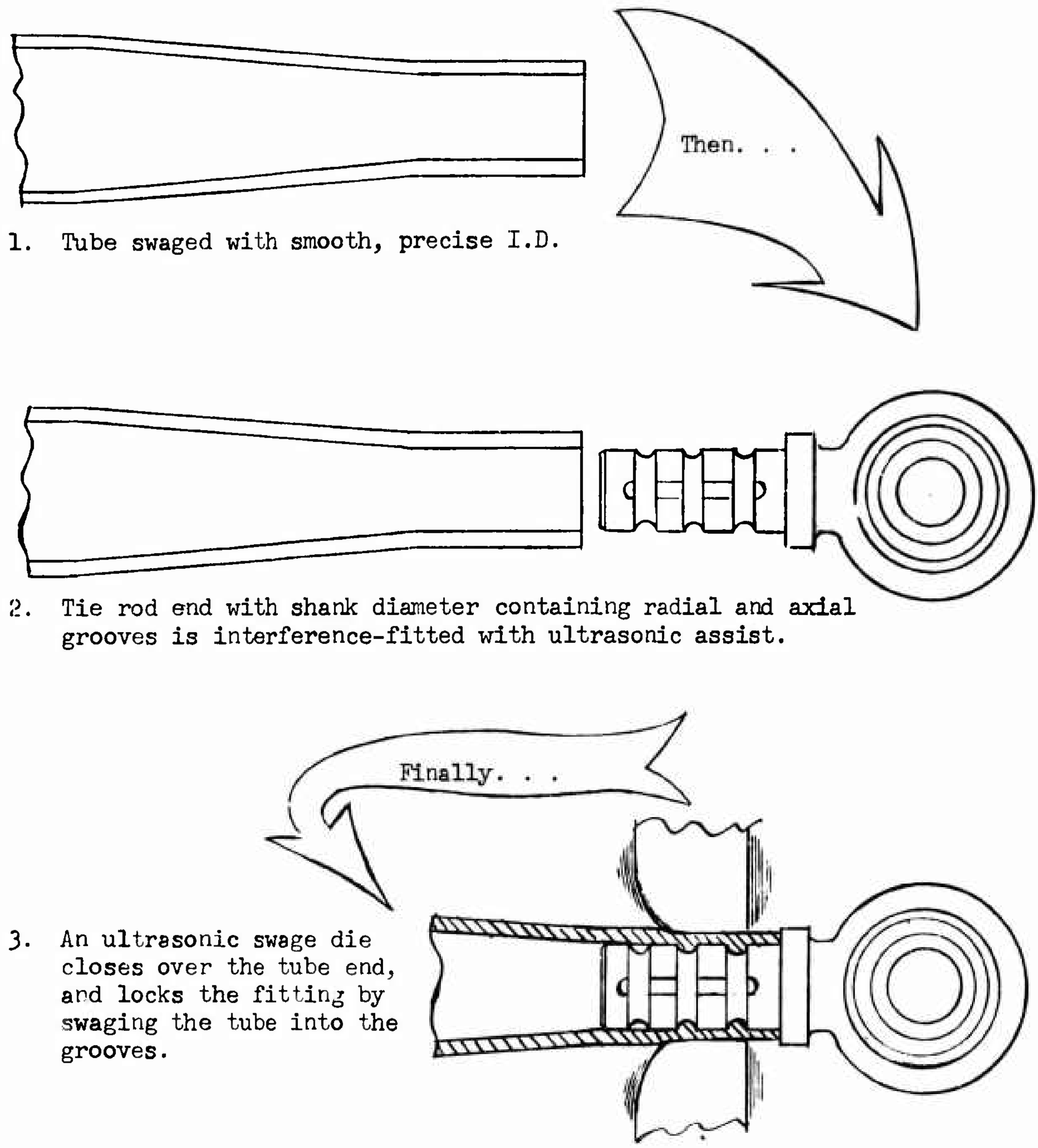


Figure 17

PROPOSED ULTRASONIC CONTROL ROD INSTALLATION

By developing ultrasonic swaging to perform this operation, there is high potential for improving manufacturing reliability, thereby reducing the present excessive scrap rate. Of greater importance is the probability than a manufacturing labor reduction of up to 50 percent could be effected. The net results are obvious: higher productivity and reduced cost per part, as shown in Table X.

B. Example II

In this configuration, the control rod end is an aluminum forging, with an AM-355 steel tube inserted in it. The tube and rod end are secured together with four aluminum rivets, as shown in Figure 18.

1. The Condition

The rod ends and tubes (in lengths up to 20 feet) must be assembled, positioned, and held accurately for cross-hole drilling. Four holes are drilled, two each 90 degrees opposed, for aluminum rivets. The rivets are inserted and cold-headed to complete the assembly.

2. The Problem

Drilling the aluminum forging presents no difficulty. The AM-355 tube, however, requires heavy drilling pressure, which deforms the unsupported side of the tube. When the drill breaks through under the extreme drilling pressure, the linear surge of the drilling machine frequently results in damage to one or both flutes of the drill. The chipped cutting edges in turn create uneven cutting pressure which causes the drill to "orbit" around its axis, thereby abrading the walls and boring an oversize hole. The problem is definable, therefore, as one not only of broken drills, but also of oversize holes, which frequently cause rejection of an expensive assembly.

3. The Solution

Drilling of the cross-pin holes would be accomplished with an ultrasonically activated drill to minimize the breakthrough problem. With the cutting forces lowered, the drill would penetrate the forging and the upper wall of the AM-355 tube without deformation or chipping. Ultrasonically assisted drilling will probably not reduce the manufacturing time needed; rather, it will improve productivity and reduce costs by lowering both tool breakage and part rejections.

4. Discussion

Contemporary theories of metal removal indicate three separate sources of heat, each of which is derived from and proportionate to the input of mechanical energy: (1) heat of deformation, induced by the generation of sufficiently high local pressure at the cutting edge to exceed the compressive yield strength of the metal, causing it to "slip" at its grain boundaries and separate, forming a chip; (2) heat of friction, caused both by the cutting tool sliding on the workpiece and the chip sliding against the tool; and

Figure X

CONTROL ROD FABRICATION
COST ANALYSIS AND COMPARISON

Present Method

	Operation	Time (minutes)	Cost
1.	Cut tube to length, swage both ends	10	$2.50
2.	Lathe fixture and tap each end of tube @ 8 minutes per end	16	4.00
3.	Screw in fittings and jamb with locknut	2	0.50
	Totals	28	$7.00

Proposed Ultrasonic Method

	Operation	Time (minutes)	Cost
1.	Cut tube to length, swage both ends	10	$2.50
2.	Ultrasonically press-fit fittings in each end @ 1 minute per end	2	0.50
3.	Ultrasonically swage tube on fittings @ 1 minute per end	2	0.50
	Totals	14	$3.50

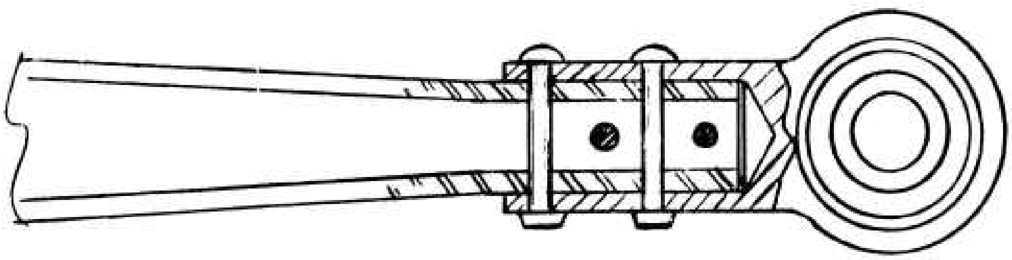


Figure 18

PRESENT RIVETED CONTROL ROD ASSEMBLY

(3) heat of compression, caused by secondary working of the chip as it curls, sliding along the tool face.

In soft, ductile materials such as aluminum or copper, chips form easily in long "stringers" without much heat generated. By comparison, the ductile, high-strength alloys such as AM-355 form a continuous chip but require extremely high energy input levels, and considerable heat is generated during machining.

In this case, it is thought that the tube wall is depressed by the high axial drill pressure as a result of the forces described above. As the point of the drill breaks through, there is a sudden reduction in chip width. There is also a forward surge of the drilling spindle and an upspring of the tube wall as the pressure is relieved. The corners of the drill are frequently chipped by the sudden too-heavy chip load.

The ultrasonic assist greatly reduces the pressure needed to drill the hole. It cannot reduce the force needed to separate the metal and form the chip, but it does reduce the friction between the drill and the chip, and causes the chip to break up into small segments. The friction is reduced by the ultrasonic vibration at the tool-work interface, and the chip breaking is assumed to be induced by the low friction level. By eliminating the compression and smearing of the chip, common to conventional removal, the chip breaks at its natural cleavage planes which are developed during the original cutting.

The assembly, drilling, and reaming times (per hole) will not be significantly reduced by changing from the present method to ultrasonic drilling. It is known, however, that manufacturing costs could be dramatically reduced (up to $64.80 per ship set) by eliminating scrap and rework of parts, and productivity could be increased by 20 to 25 percent (see Table XI).

The ultrasonic addition to conventional drilling equipment will add somewhat to its overall size and bulk, although not enough to be a hindrance to the stationary bench-type machines used for this operation.

5. Equipment Definition

Ultrasonic technology and equipment designs are available, but some modification to standard equipment will be required (Category B). Equipment cost will be in the vicinity of $4000 to $5000, and 3-4 months will be required for fabrication.

Table XI

CONTROL ROD FABRICATION
COST OF REWORK AND REJECTS

Estimated: (a) 24 control rod assemblies per ship with 8 rivets per assembly

(b) 33% (8 assemblies) are rejected for oversize holes

(c) 4 of the 8 rejected assemblies are scrap

(d) 6 broken drills

			Cost
1.	Cost to inspect, remove broken drills, and redrill to next larger (repair) size	4 parts @ 20 minutes per part ($0.25/minute)	$20.00
2.	Cost of M-42 HSS drills	6 drills @ $0.80 each	4.80
3.	Total rework cost per ship		$24.80
4.	Estimated cost of 4 scrapped parts	$10.00 each	40.00
5.	Total cost per ship		$64.80

IV. BEARING RETAINER INSTALLATION

A. The Example

The aluminum tail rotor hub has a hardened steel bearing retainer installed in the bore, as shown in Figure 19.

B. The Condition

To avoid fretting or galling of the parts during installation, the retainer is cooled to -320°F in liquid nitrogen and the hub is heated to 250°F in an oven. Shrink-fitting is accomplished in a hydraulic press, with the hub positioned in a fixture and the retainer placed on a mandrel.

C. The Problem

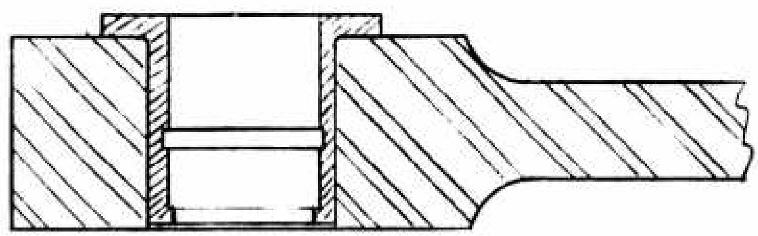
Without the temperature differential to allow press fitting, damage to one or both parts due to galling is virtually certain. The necessary preparation requires an estimated 30 minutes elapsed time to make ready (cooling and heating), with approximately 50 percent of this time being consumed by labor.

When the parts are ready for assembly, they must be handled expeditiously to prevent decay of the temperature differential. The hub must be fixtured and the retainer position on the mandrel, and press fitting the retainer into place is accomplished very quickly. Should the retainer become "cocked" or misaligned at this point, the bore will be scored and a very expensive assembly will have to be scrapped.

As the respective parts return to ambient temperature, it is often found that shrinking of the hub and expanding of the retainer combine to produce a small gap between the retainer flange and the hub surface (Figure 20). This affects both the structural and dimensional integrity of the assembly, and expensive rework is frequently required to correct this condition by again pressing the retainer to close the gap. It has been conservatively estimated that 15 percent of the assemblies require rework and that an additional 5 percent are scrapped because of misaligmment.

D. The Solution

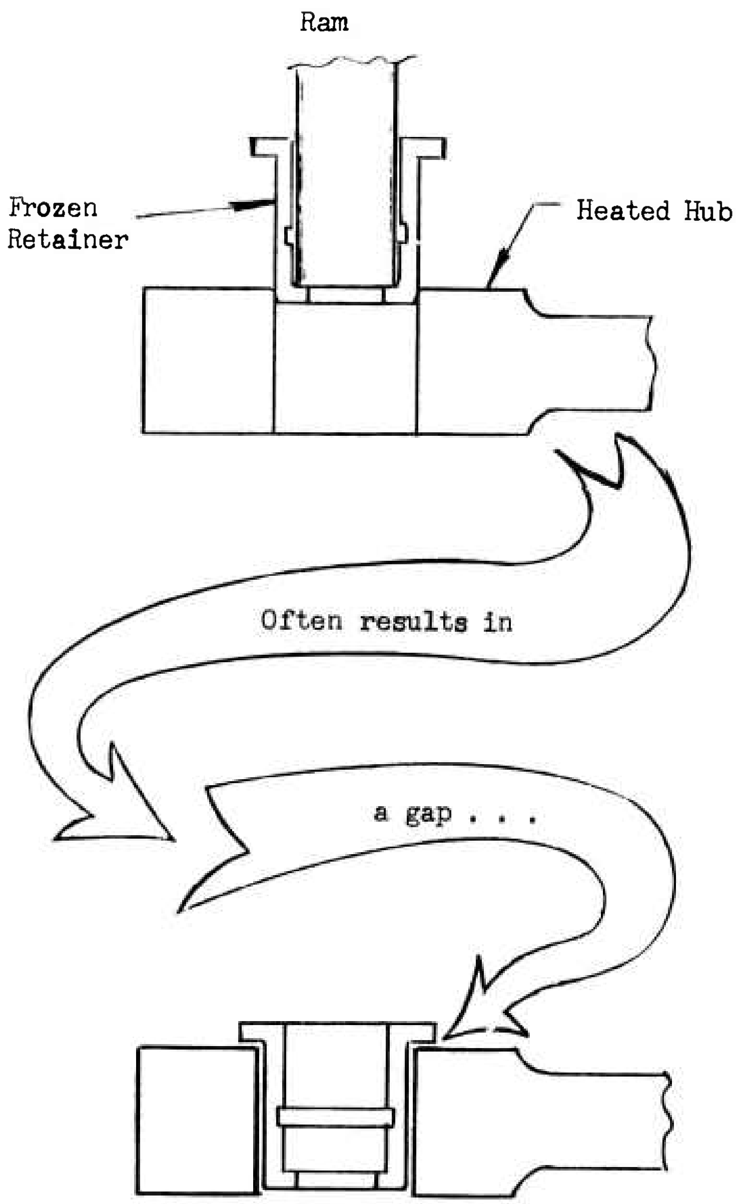
With ultrasonic activation of the installing ram, these bearing retainers can be installed quickly and easily at room temperature, thereby eliminating the expensive heat-up/cool-down cycles, and the flange can be brought into firm contact with the hub face each time.



Sectional sketch showing bearing retainer installed with flange in solid contact with hub

Figure 19

TAIL ROTOR HUB WITH BEARING RETAINER



The gap causes an out-of-tolerance condition. Before use, the retainer must be restruct to be seated.

Figure 20

PRESENT BEARING RETAINER INSTALLATION

E. Discussion

Press fitting bearing races and retainers into mating assemblies is so commonly done today, it is difficult to think of it as a problem. However, the combinations of aluminum and titanium rotor hubs and hardened bearing components make interference fitting difficult. The negative allowances (up to 0.006 inch) tend, on press fitting, to extrude or gall the softer metal. The galling, if detected, will result in rejection; if not detected, experience shows it can cause eventual part failure.

When using ultrasonic energy to assist in interference fitting, friction between mating members is greatly reduced. The added energy makes interference assembly possible without (1) galling, (2) labor expense of heating and cooling in preparation, and (3) restriking (see Table XII).

The equipment needed to perform these operations would be a C-frame press in the 10-ton to 25-ton range. It should be made large enough to accommodate a broad variety of parts. Interchangeable tooling, such as holding fixtures and installing mandrels, could be made in sizes to perform various operations, thereby increasing equipment utilization.

F. Equipment Definition

Technology for this operation is available, but the ultrasonic equipment will require specific design for installation on an existing press (Category B). Estimated cost for such equipment is about $5000.00 and delivery time would be 4-5 months.

Table XII

BEARING RETAINER INSTALLATION
COST ANALYSIS AND COMPARISON

Present Method

	Operation	Elapsed Time (minutes)	Labor Cost
1.	Place bearing retainers in LN_2	--	--
2.	Place hubs in oven at 250°F (30 minutes elapsed time, 15 minutes labor)	30	\$ 3.75
3.	Fixture hub and retainer	5	1.25
4.	Install	3	0.75
	Totals per Part	23	\$ 5.75
5.	Production rate, 110 tail rotors per month, including spares: 110 x \$5.75		\$632.50
6.	15% (16.5 parts) requiring rework (#3 + #4)	132	33.00
7.	Inspection on reworked parts at 5 minutes per part	82.5	20.63
	Total cost per month		\$686.13

Proposed Ultrasonic Method

	Operation	Elapsed Time (minutes)	Labor Cost
1.	Fixture hub and retainer	5	\$ 1.25
2.	Install	3	2.50
	Totals per Part	8	\$ 3.75
3.	Production rate, 110 parts per month		\$412.50
	Total cost per month		\$412.50

V. MAIN ROTOR BLADE ASSEMBLY

A. The Example

The main rotor blade is composed of an aluminum skin, a stainless steel abrasion strip, an aluminum honeycomb core, the end cap, the trailing edge forging, and a series of doublers to which the root fitting is attached (Figure 21). The entire assembly is epoxy-bonded, after being carefully laid up in a very precise fixture, clamped, and loaded into an oven.

B. The Conditions

The skin of 2024 aluminum alloy, approximately 28 inches by 20 feet, is finish-sized and partly shaped to the finished airfoil configuration. Because of its size, it is difficult to handle and will not conform to the finished blade contour without support. The present practice is to load the fixture with the skin, the epoxy adhesive, the honeycomb (also of 2024 aluminum alloy, in 0.005-inch foil thickness), and the other parts, less the doublers. After tack-bonding the blade components into position, the seven doublers (2024 aluminum alloy, 0.040 inch thick) are individually located on the root of the blade along with the epoxy adhesive. The fixture is closed and clamped and then placed in the oven for curing the epoxy.

C. The Problem

The skin and honeycomb, because of their nature in the unsupported state, are difficult to handle and make conform to the bonding fixture. To aid in lay-up of the blade, an electrical heatgun is used to soften the adhesive and permit tack-bonding.

The low density and high heat conductivity of the metals used make localized temperature control during gun-heating very difficult. The adhesive softens and becomes tacky between 150° and 200°F, but the heat is dissipated so rapidly that heating the skin to an even temperature is nearly impossible. If a localized area should be inadvertently heated to 285°F, the adhesive will harden and then will not bond during oven-curing. The result is an unbonded spot or series of spots that are detected by ultrasonic inspection, causing blade rejection.

D. The Solution

A portable ultrasonic "gun" could be developed to spot-bond the adhesive and hold the blade subassembly (without the doublers) together. This would permit assembling the components quickly, easily, and accurately.

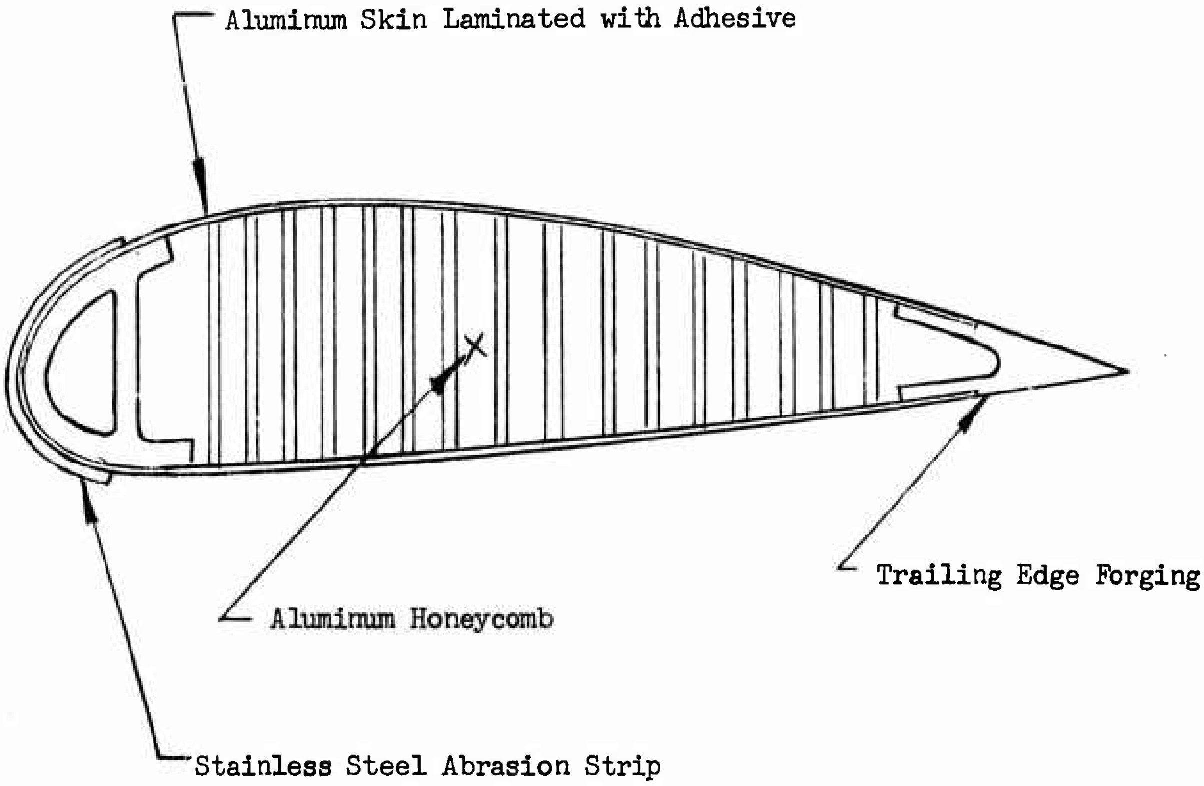


Figure 21

CROSS SECTION OF BONDED MAIN ROTOR BLADE, LESS DOUBLERS

In addition, a "hard" fixture could be used to assemble the several layers of the doubler for ultrasonic tack-bonding. By doing so, each of the doublers could be made to conform to the desired shape, and, after tacking, the subassembly would be fitted to the laid-up blade for oven-curing of the adhesive (see Figure 22).

E. Discussion

Ultrasonic tack-bonding of the doublers on a hard fixture is well within existing technology, and equipment is available for this application.

Ultrasonic bonding without a hard backup may require some development effort, since normally the process involves rigidly supporting one member while oscillating the other. The blade assembly before bonding is less than rigid, although the bonding film supplies some rigidity due to its natural tackiness.

However, the present extreme labor cost, combined with the need for improvement over current manufacturing process control, gives this method a very high priority. Further incentive can be gained from the fact that the helicopter industry is today's largest user of epoxy bonding films. The technique were derived originally from contemporary fixed-wing aircraft joining methods, and both industries employ this method with increasing frequency.

The estimated cost comparison in Table XIII shows a labor cost reduction per blade of $6.75. With a production rate of 15 ships per month plus 4 sets of spares per ship (150 blades per month), the savings in labor costs would amount to $1012.50.

It was observed above that occasionally the operator will inadvertently overheat localized areas of the blade with the heat gun, causing the adhesive to cure prematurely. After vacuum bonding, a bubble may be detectable in this area between the skin and honeycomb interface. Large sizes or frequencies of unbonded areas result in rejection of the bonded blade at this point. Such scrap may cost as much as $1500 per blade. It is estimated that 5 percent of the present production is lost due to this problem; thus the scrap loss may amount to as much as $10,000 per month.

F. Equipment Definition

Ultrasonic welding equipment for bonding the doublers on a hard fixture (Category A) should probably have a power capacity of 1000 to 2000 acoustical watts. Such equipment would cost up to $25,000, and delivery could be made in 4-6 months. (This equipment would be useful for other purposes as well.)

As noted, some development would be required for tack-bonding the less rigid assemblies (Category C), but final equipment cost should be approximately the same as above.

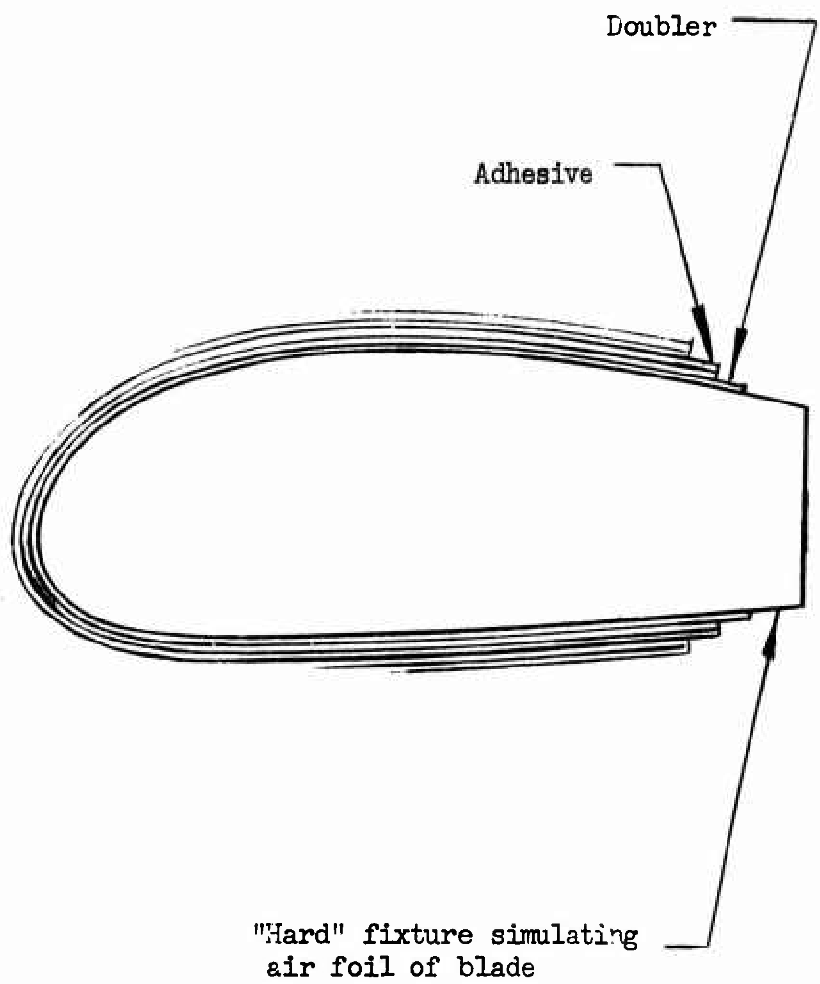


Figure 22

PROPOSED ULTRASONIC TACK-BONDING CONCEPT
OF DOUBLER PREBONDING LAYUP

Table XIII

MAIN ROTOR BLADE BONDING COST ANALYSIS AND COMPARISON

Operation	Present Method Time (minutes)	Present Method Cost	Ultrasonic Tack-Bonding Time (minutes)	Ultrasonic Tack-Bonding Cost
1. Locate preformed skin in fixture	5	$ 1.25	5	$ 1.25
2. Position bonding film on skin	10	2.50	10	2.50
3. Position trailing edge "arrowhead" on skin	2	0.50	2	0.50
4. Position preformed honeycomb core in fixture	10	2.50	10	2.50
5. Position outboard end-cap fittings	5	1.25	5	1.25
6. Manually wrap, position, and heat-gun tack skin on upper honeycomb surface	30	7.50	--	--
7. Manually wrap, position, and ultrasonically tack-bond skin on upper honeycomb surface	--	--	3	0.75
Totals	62	$15.50	35	$ 8.75

Savings per blade with ultrasonic tack-bonding: $6.75

VI. TORQUE WRENCHING

A. The Examples

1. The main rotor transmission case is mounted in the ship with a series of 3/4-inch to 1-inch-diameter high-strength bolts. The case itself is assembled with the same type of fasteners. These bolts are torqued to extremely high levels, approaching 80 percent of the tensile strength of the fastener material.

2. Titanium alloys and boron composites are being increasingly used in aircraft because of their high strength-to-weight ratios. Assembly of these materials involves the use of small, highly torqued bolts.

3. One manufacturer employs a very large (6½ inches) hexagonal nut to secure the main rotor hub to the shaft. The philosophy of a large threaded fastener quite obviously is to obtain high clamping pressure, while affording fast removal and replacement of the rotor hub.

B. The Conditions

1. Both the engine and the transmission are secured within the ship in very limited areas. The torque requirements of the fasteners range from 350 to 800 foot-pounds. The torque wrenches used are large, and extreme physical effort is needed to achieve the necessary tightening. Such conditions dictate either frequent operator alternation or two or more people working together.

2. The contemporary method of assembling the very-high-strength materials into the structure is to employ hundreds, and often thousands, of small to medium-sized (3/16-inch to 1/2-inch diameter) countersunk bolts. The bolts are installed individually by hand and torqued with a preset, self-releasing torque wrench.

3. Working on a scaffold 20-25 feet above the floor, four men are required on a double-handled torque wrench, which is 8 feet long, to secure the main rotor hub to the shaft. During assembly, a fifth worker (inspector) is required to certify that the desired torque range has been reached.

C. The Problem

In each of the above areas, the problems are similar: Working space is restricted, while a heavy, long-handled wrench is needed; there is limited access for leverage; the self-releasing type of wrench used at present produces wide ranges of torque values and needs frequent recalibration; and last but most important, very high manpower requirements are essential for torquing.

D. The Solution

A series of ultrasonic torque wrenches should be developed to perform a broad range of torquing operations. Stuides have shown that ultrasonic activation can dramatically reduce the physical effort needed to obtain a given torque value (Appendix B, Ref. 382-389). Sufficient data have been compiled to indicate a significant reduction in human energy input in torquing and untorquing of fasteners. Thus labor costs would be reduced while the reliability factors of torquing are improved.

E. Discussion

Prior ultrasonic wrenching developments specifically pertain to flared tube fittings, and it was observed that, after the desired torque level is attained, wrenching must be discontinued to avoid deformation of the tubing. The high-strength fasteners referred to in this study have no such limitation; rather, the intention is to tighten them until their yield point is approached.

It appears entirely feasible to reduce the manual-force input on a 800-foot-pound wrench, for example, by 50 percent through ultrasonic application at power levels up to 1000 acoustical watts (somewhat in excess of 1 horsepower). Such reduction in the required human input could be interpreted several ways: either the operator's work may become easier, or the wrench may be shortened, or a combination of both.

Another promising aspect of an ultrasonic torque wrench, also confirmed in prior studies, is improved control of the torque to achieve the desired tension in the fastener assembly; this would result in a smaller torque allowance than is presently possible.

Up to this point, the discussion of torquing has been concerned with fastener assembly. Loosening of tightened fasteners can also be difficult. The same space restrictions and awkward working conditions prevail, and the necessary torque levels are often higher due to the tendency of the nut to "freeze." In any case, the act of loosening such fasteners is always very fatiguing, resulting in low operator output, with corresponding increase in cost.

The required effort to solve these problems would consist of developing ultrasonic wrenches of several sizes. These would include tools for ranges of 0-500 foot-pounds, 500-1000 foot-pounds, and 1000-2000 foot-pounds. For each of these torque levels, socket wrench extensions of up to 12 inches may be necessary to reach into confined areas.

F. Equipment Definition

While past endeavors in ultrasonic wrenching have been successful, the torque levels have been low (about 500 foot-pounds maximum), and space limitations have not been a consideration. The higher torque levels presently needed, together with required tool configurations, will require further research and development (Categories C to D).

VII. ULTRASONIC TURNING AND BORING

In today's highly efficient metal removing technology, it is sometimes hard to think of problem machining areas that are slow and costly. The new generation of machines and cutting tools is remarkably efficient. The machines are fast, powerful, and accurate. The cutting tools are extremely durable, and their development has contributed much to the incentive for developing faster and better machines.

In the production of automotive, agricultural, and domestic appliances, metal removal has been refined to a high degree. Cast iron engine blocks, with all their complexity, are machined with high precision at the rate of two and sometimes three per minute. Full transmission and differential sets of gears for automobiles are machined, heat-treated, and lapped at the same rate. Small electric motor components are semi-automatically produced at the rate of 100 per hour, with tool changes needed only once in 8 hours.

The philosophy of the helicopter industry, derived from and closely related to that for aircraft, creates quite a different set of working conditions and parameters. The ultimate helicopter part configuration would have 100 percent strength and reliability factors at zero percent weight. Although obviously impossible, the design engineers constantly strive toward this goal. Lighter, stronger materials are used; hardnesses are increased by either heat treatment or material nature or both. Walls become thinner, sections become narrower, and configurations more complex.

With increasing frequency, the design engineer's concepts involve these exotic materials and critical strength levels. Some such parts are virtually impossible to make using conventional methods. There is no doubt that these parts can eventually be made. It is therefore necessary to qualify the "virtually impossible" with one or more of the following conditions:

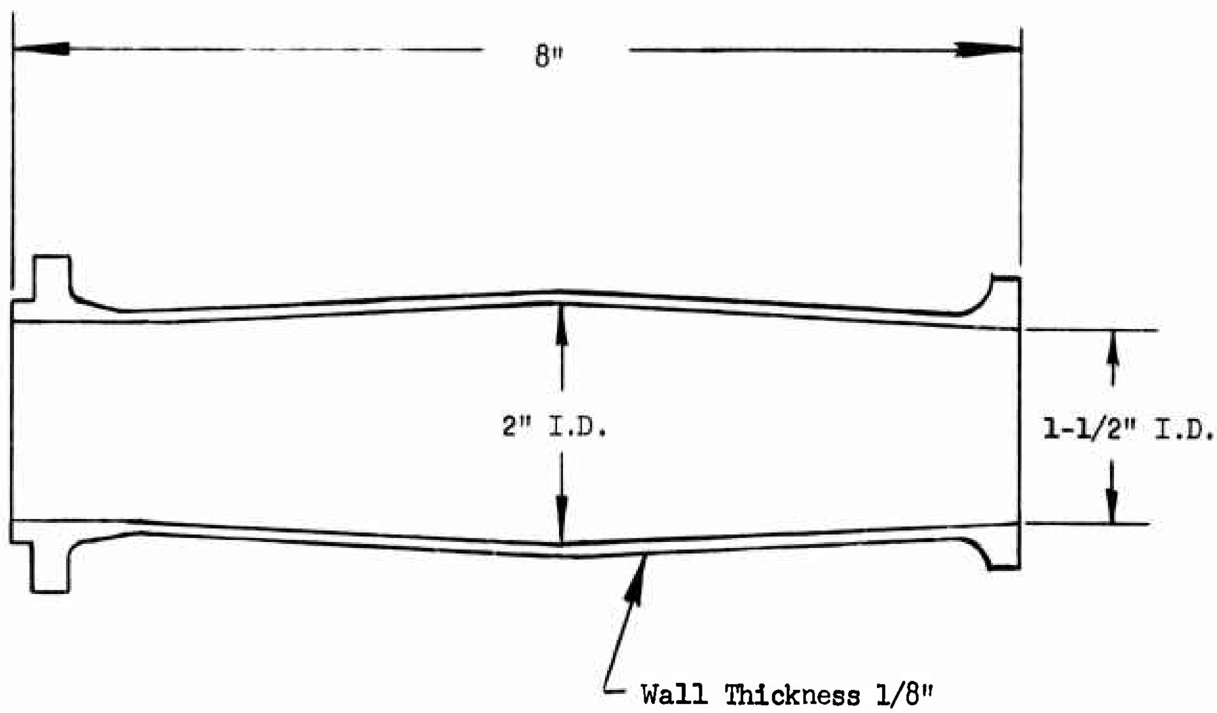
1. Existing methods and tools may not be able to hold the required tolerances or produce the required surface finishes due to workpiece deflection, tool chatter, or boring bar deflection. Necessary secondary and post-secondary finishing operations therefore reduce productivity and increase cost.

2. Tool chatter or deflection may cause premature cutting-tool failure, adding to both tool and labor costs.

3. Light cuts and low surface speeds may be required to reduce or eliminate Items 1 and 2 above. This in itself may double or triple the labor cost per part.

A. The Example

The part shown in Figure 23 has been selected for a comparison of conventional versus ultrasonic machining. This represents one of the more difficult part-material/configuration combinations that may be encountered.



Material: 6Al-4V Titanium Alloy

Figure 23

SAMPLE MACHINED PART CONFIGURATION

B. The Problem

This part is long and thin-walled, making it flimsy; it is made of 6Al-4V titanium alloy, one of the more difficult-to-machine alloys; and it requires both inside and outside contour machining. The inside shape is particularly difficult, due to the enlargement at the "beltline," which requires a long, slender boring bar. With conventional machining, this example reflects increased manufacturing costs due to all three problem conditions listed above.

C. The Solution

Ultrasonically assisted machining of this part or others similar to it would be expected to provide one or more of the following advantages:

1. Reduced time to make the part (higher feed rate, depth of cut, or surface speed).
2. Improved surface finish and dimensional control.
3. Extended tool life.
4. Reduced scrap, or fewer parts requiring rework.

D. Discussion

A study was made of the major machining operations required to make this part in order to illustrate how ultrasonics can be applied to alleviate the manufacturing problems and reduce the cost of such machining. Table XIV provides a comparison of conventional machining rates* and the projected rates with ultrasonic activation.

1. Drilling

   Two drilling operations would be required: first, a pilot drill (3/4 inch) followed by the pre-boring drill (1-7/16 inch).

2. Boring

   To bore the part, it is estimated that a 1/1/8-inch-diameter bar would be the maximum possible, with the cutting tool protruding from the bar 5/16 inch. It is known that under normal conditions, boring can be accomplished without difficulty. The long slender boring bar, however, undoubtedly would require both reduced surface speed and reduced depth of cut. In combination, these are estimated to increase the time per part by a factor of four.

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* Machining Data Handbook, METCUT Research Associates, Inc., 1972, p. 250.

Table XIV

DRILLING, TURNING, AND BORING COST ANALYSIS AND COMPARISON

Operation	Present Methods: Parameters	Present Methods: Time (minutes)	Present Methods: Cost	Ultrasonic Methods: Parameters	Ultrasonic Methods: Time (minutes)	Ultrasonic Methods: Cost
1. Pilot drill 0.750-inch diameter	178 rpm @ 0.007 ipr	6.42	$ 1.61	178 rpm @ 0.011 ipr	4.08	$ 1.02
2. Bore drill 1.44-inch diameter	93 rpm @ 0.010 ipr	8.60	2.15	93 rpm @ 0.015 ipr	5.81	1.45
3. Rough bore	0.050-in. depth of cut 187 rpm @ 0.004 ipr Est. 9 cuts, 44 in. total	58.80	14.70	0.100-in. depth of cut 347 rpm @ 0.009 ipr 20 in. total	6.40	1.60
4. Finish bore	200 rpm @ 0.005 ipr	8.00	2.00	400 rpm @ 0.005 ipr	4.00	1.00
5. Rough turn O.D.	420 rpm @ 0.007 ipr 20 in. total	6.80	1.70	420 rpm @ 0.007 rpm 20 in. total	6.80	1.70
6. Semi-finish turn O.D.	420 rpm @ 0.007 ipr 0.025 in. depth of cut	5.44	1.36	Omit	--	--
7. Finish turn O.D.	420 rpm @ 0.007 ipr	2.72	0.68	420 rpm @ C.007 ipr	2.72	0.68
Totals		96.78	$24.20		29.81	$ 7.45

3. Turning

Although the outside configuration is the easiest of the three major machining operations, it, too, requires care to avoid damaging the part. As the wall approaches its final thickness, normal cutting pressures will deflect the thin material. The result will be a damaged part, or at best one requiring a post-finishing operation.

The comparative totals in Table XIV show that by applying ultrasonics during drilling, boring, and turning, the cost of these operations can be reduced by as much as 75 percent. When the costs of rejected or damaged parts, together with the comprehensive manufacturing time, are totaled, the comparison becomes even more favorable.

E. Equipment Definition

The above-described operations would presumably be done in a conventional manner in a hydraulic profile lathe, costing approximately $30,000. Designs for ultrasonic tool posts and boring bars adaptable for installation on the lathe are available (Category A). Cost of one tool post, one boring bar, and a frequency converter for driving either system is in the vicinity of $25,000, and delivery can be made in about 4 months.

APPENDIX B

ANNOTATED BIBLIOGRAPHY ON ULTRASONIC APPLICATIONS IN METALWORKING PROCESSES

I. INTRODUCTION

The background of development leading to the present status of ultrasonic metalworking is reflected in the scientific and technical literature dating back to the 1930's. This Appendix B presents abstracts of pertinent documents generated in the United States as well as foreign countries, primarily Great Britain, Germany, France, Russia, and Japan. Books, journal articles, technical papers, project reports, and patents, identified from a variety of documentary sources (listed in Appendix C) have been reviewed and the most significant included herein.

The abstracts are segregated with respect to the type of metalworking process involved and arranged chronologically within each area to provide a sense of its historical development. Book, periodical, and report literature is presented in Section II, and patent literature in Section III.

Although emphasis has been placed on the literature generated in the United States, significant foreign work is also included to the extent available, because some of the processes had their inception in other countries and a few have been pursued more vigorously elsewhere. Many English translations of these foreign documents were available from translation sources; a number of French and German and a few Russian documents have been specially translated; and English abstracts have provided a further source for foreign literature. All titles are given in English, and outside translation sources are noted where applicable.

The total body of literature assembled, amounting to more than 2000 titles, was obviously too voluminous to include; much of it would contribute little to the evolutionary picture of the various processes or to the basic objectives of this study. In accordance with the guidelines presented in the Introduction (page 1), we have deleted references relating to:

1. Ultrasonic slurry machining, variously called ultrasonic machining, cavitation machining, ultrasonic grinding, ultrasonic or vibratory lapping, or impact drilling.

2. Ultrasonic plating and electrodeposition.

3. Ultrasonic joining as applied to microelectronic devices.

4. Ultrasonic weld encapsulation of ordnance devices.

5. Ultrasonic plasticity and friction reduction (basic mechanisms in many of the ultrasonic effects) unless oriented to some specific process.

6. Low-frequency vibratory processing, usually in the range of a few hundred hertz.

The remaining references were carefully screened to include generally only original source materials, to combine items containing generally the same information, and to eliminate reviews that contribute nothing new, items without scientific significance, or successive progress reports where a final report was available.

Review of the literature indicates that ultrasonic metalworking received little attention prior to about 1950. Ultrasonic soldering and fusion welding were investigated to a limited extent in Germany, and a few sporadic publications on metal forming and metal removal appeared. The 1950's saw some increase in activity in all areas, but primarily associated with the introduction of ultrasonic soldering into production use and the development of ultrasonic welding; investigators also began to look more closely at metal removal processes. The real impetus came in the 1960's when consideration was given to the basic mechanisms and production potential over the whole range of metalworking areas, and in some instances (primarily ultrasonic welding, tube drawing, wire drawing, core drilling, and metal finishing), production equipment and techniques were evolved. The progress of evolutionary development, as reflected in the significant published documents, is shown in Figure 24.

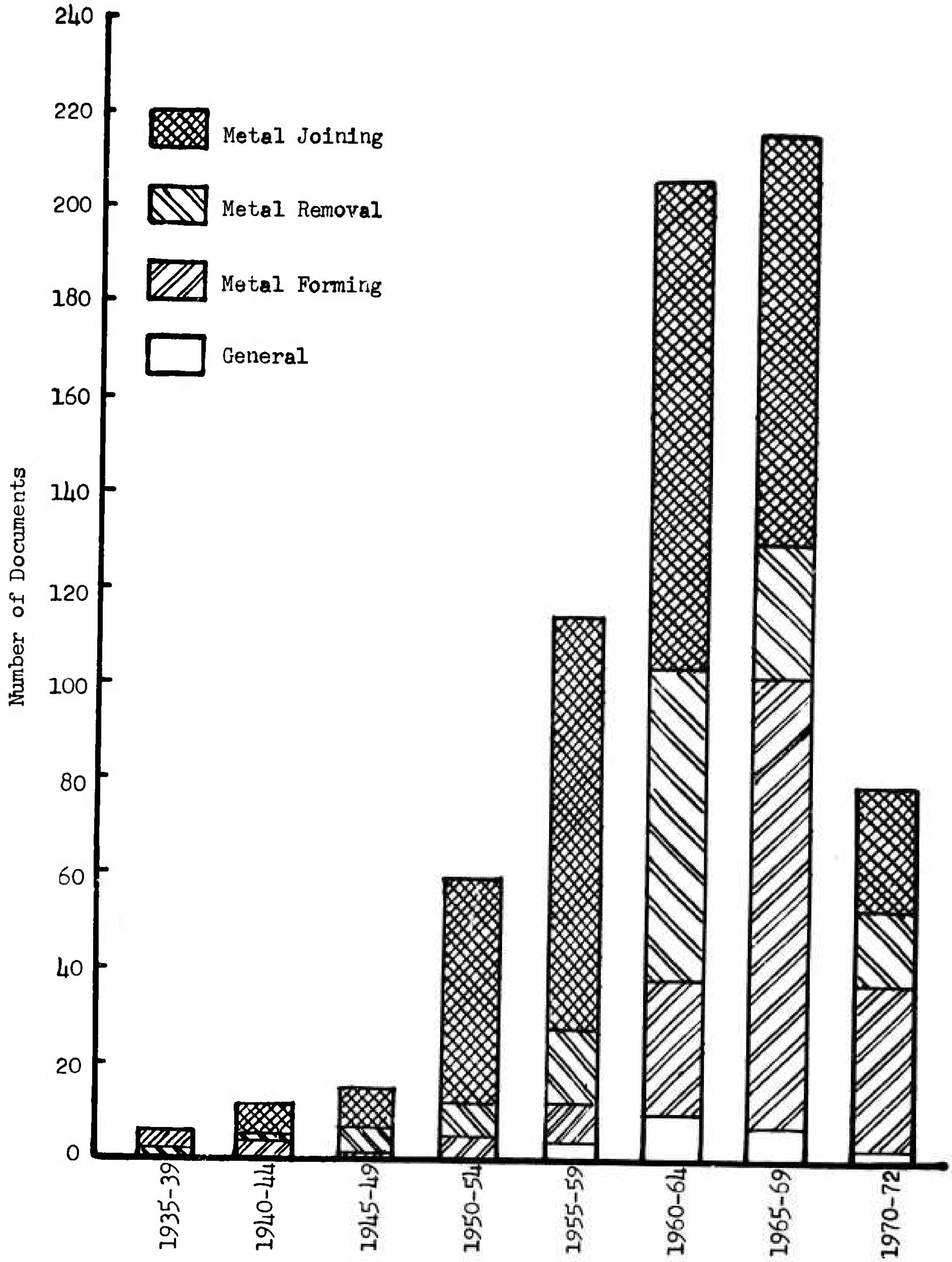

Figure 24

SIGNIFICANT DOCUMENTS ON ULTRASONIC METALWORKING
PUBLISHED FROM 1935 TO 1972

II. BOOK, PERIODICAL, AND REPORT LITERATURE

This presentation of the general literature on ultrasonic metalworking covers primarily results of research and development on the various processes, significant equipment development and engineering, and projected or actual production uses. The entries are grouped under the major headings of Metal Forming, Metal Removal, and Metal Joining, with subheadings under each. A General category at the beginning includes references dealing with more than one of the three categories, and a General heading under each category includes references dealing with more than one of the processes thereunder.

Some entries appear more than once, where they provide significant information on more than one process. In other instances, where duplicate information appears in more than one reference, two or more entries may be combined.

The abstracts are numbered consecutively, as follows:

Subject		Ref. Nos.
A.	GENERAL	1-9
B.	METAL FORMING	
	General	10-18
	Tube Drawing	19-40
	Wire and Rod Drawing	41-69
	Extrusion	70-73
	Rolling	74-83
	Forging	84-96
	Riveting	97-103
	Stretch Forming	104-112
	Bending and Straightening	113-114
	Powder Metallurgy	115-130
C.	METAL REMOVAL	
	General	131-136
	Turning	137-152
	Drilling	153-168
	Milling	169-172
	Broaching	173
	Thread Cutting	174-180
	Grinding	181-192
	Finishing	193-204

D. METAL JOINING

A. GENERAL

1. Ames, R. S., J. B. Jones, and F. R. Meyer, "Ultrasonic Metal Joining and Machining." SAE Paper 483D, Automotive Engineering Congress, Detroit, Jan. 8-12, 1962.

A comprehensive review of the status, techniques, equipment, and applications of ultrasonic welding, soldering, slurry machining, and deburring was presented. These processes were noted to supplement rather than replace the more conventional joining and machining techniques and find their most effective application where other methods are costly, impractical, or unsuccessful.

2. Rosenfield, A. R., "The Application of Ultrasonic Energy in the Deformation of Metals." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963.

This informal symposium, sponsored by the Navy Bureau of Naval Weapons as part of the Metalworking Process and Equipment Program (MPEP), included reports from investigators actively engaged in applying ultrasonics to such processes. Papers were presented on ultrasonic effects on material properties, metal cutting, wire drawing, tube drawing, extrusion, and other metal forming and metal removal processes. (Significant papers are abstracted separately.)

3. Balamuth, L., "Recent Developments in Ultrasonic Metalworking Processes." SAE Paper 849G, Air Transport and Space Meeting, New York, April 27-30, 1964. Also Balamuth, "Ultrasonic Metalworking." American Machinist, Vol. 108, April 13, 1964, p. 136-138.

Experimental results were presented covering ultrasonic application to metal removal processes, including single-point machining, milling, broaching, lapping, and honing; to metal forming processes such as extrusion and wire flattening; and to metal joining. The required equipment was noted to include an electromechanical transducer, a mechanical impedance transformer, and the tool.

4. Neppiras, E. A., "Ultrasonic Machining and Forming." Ultrasonics, Vol. 2, Oct. 1964, p. 167-173.

This review was concerned primarily with slurry machining; brief mention was also made of ultrasonic application to grinding wheels, lathe tools, milling cutters, reamers, and lapping plates, and to press forming and drawing operations. Ultrasonics combined with electrolytic machining was noted to offer significant potential in increased machining rate and reduced tool wear.

GENERAL

5. Aeroprojects Inc., "The Application of Vibrational Energy to the Drawing of Metallic Materials, Phase I." Report IR-8-191(I), Air Force Contract AF 33(615)-2169, Feb. 1965.

A survey was made of application of vibrational energy (both low and high frequencies) to metal forming and metal removal processes, including vibrational effects on interfacial friction and metal plasticity, considered the basic mechanisms in these processes. Information was presented on process parameters and force reductions, problem areas and proposed solutions, and the design of equipment to be used in evaluating ultrasonic wire and rod drawing.

6. Kristoffy, I. I., R. L. Kegg, and R. R. Weber, "Influence of Vibrational Energy on Metalworking Processes." Report AFML-TR-65-211, Cincinnati Milling and Grinding Machines, Inc., Cincinnati, Ohio, Air Force Contract AF 33(657)-10821, July 1965.

Investigations in ultrasonic metal forming and cutting were carried out to obtain a better understanding of the mechanisms involved, to demonstrate practical techniques of application, and to determine the benefits obtainable. Vibration at 20 Hz, 1000-3000 Hz, and 19-26 kHz was applied during cup drawing, draw ironing, forging, and lathe turning. In all cases, apparent force reductions were obtained, generally attributed to the replacement of part of the static force with dynamic force. It was suggested that the size of massive metalworking equipment could be reduced by this means.

7. McMaster, R. C., "Sonic Power--University Research With an Industrial Payoff." News in Engineering, Ohio State University, July 1967, p. 1-8.

Ruggedized 10-kHz sonic motors (transducers) covering the power range up to 15 hp were developed for heavy-duty industrial processing. Such systems were said to be effectively used to reduce frictional forces between work materials and tools in relative motion. Local stress concentrations were thus alleviated and workpiece damage did not occur. Such effects could be used in drawing, extrusion, rolling, upsetting, hot and cold forging, welding, and bonding. It was observed that static forces are thus lowered in the order of 100X, and product quality is improved.

8. Severdenko, V. P. and V. V. Klubovich, Application of Ultrasonics in Industry. Nauka i Tekhnika, Minsk, USSR, 1967, p. 83-149, 218-249. (Air Force Translation FTD-MT-24-24-69).

A comprehensive review of a variety of ultrasonic metalworking applications having potential for industrial use was presented, with voluminous literature references. Included were ultrasonic milling, grinding, soldering and tinning, welding, deburring, upsetting, drawing, extrusion, and cold pressing. It was observed that experimentation in these ares must be

continued along with theoretical studies, and the next few years should bring new discoveries in industrial use of ultrasonics.

9. Shoh, A., "New Developments in Metal Working Processes." 83rd Meeting, Acoustical Society of America, Buffalo, N. Y., April 18-21, 1972.

Experiments in ultrasonically assisted metal forming and machining were described, with emphasis on the basic physical quantities and controllable ultrasonic parameters involved. Specific examples included ultrasonic twist drilling with axial vibratory motion superimposed on the rotational motion of the drill, and deformation of cylindrical specimens as a function of static and dynamic stress.

B. METAL FORMING

General

10. Balamuth, L., "Progress in Ultrasonic Metal Forming." SAE Paper 971A, Automotive Engineering Congress, Detroit, Jan. 11-15, 1965.

The ultrasonic effects on metal deformation processes were discussed theoretically in terms of friction reduction, which lowers mechanical energy requirements, and reduction in metal shear resistance, which lowers the apparent static yield strength. Current work on ultrasonic wire drawing, extrusion, sheet metal rolling, and forging was reviewed.

11. Maropis, N. and J. C. Clement, "Transition Between Theory and Practice in Ultrasonic Metal Deformation Processing." Tech. Report C6-26.3, 1966 National Metals Congress, American Society for Metals, Chicago, Oct. 31-Nov. 3, 1966.

Ultrasonic application to metal forming processes was observed to offer such advantages as reduced processing forces, increased processing rates, greater reduction per pass, and/or an improved product. The necessity for designing ultrasonic systems specifically for the application was emphasized. The evolution from ultrasonic theory through experimentation and equipment design to production use was illustrated in terms of ultrasonic drawing of wires, rods, and tubes.

12. Severdenko, V. P., K. V. Gorov, Ye. G. Konovalov, V. I. Yefremov, and L. A. Shevchuk, Ultrasound Treatment of Metals. USSR, 1966. (Air Force Translation FTD-MT-24-439-68).

This review, prepared for research engineering personnel in the USSR, covers basic problems associated with propagation of elastic vibration in various media, design of various types of ultrasonic equipment, and applications particularly in the metallurgical industry. Discussions were included on the effect of ultrasonics on structure and properties of metals and alloys, and effects on plastic deformation. Experimental work on free upsetting of metals and on wire drawing was described.

13. Maropis, N., "The Application of Ultrasonic Vibratory Energy to Metal Drawing Processes." Master of Engineering Thesis, Pennsylvania State University, March 1967.

This study considered basic theory and practice associated with commercial drawing of metals, modifications thereto resulting from application of ultrasonic energy, and basic design considerations for ultrasonic equipment to insure maximum effectiveness. Experimental data were provided to show the effects of vibratory frequency, power, and amplitude, and the effects of drawing rate, area reduction, and surface area-to-volume ratio. Ultrasonic effects on die temperature, drawbench power requirements, and quality of the drawn materials were evaluated.

14. Winsper, C. E. and D. H. Sansome, "A Review of the Application of Oscillatory Energy to Metals Deforming Plastically." Eighth International Machine Tool Design and Research Conf., Manchester, England, Sept. 1967.

Historical development of vibratory application to metalworking processes was reviewed, with emphasis on the friction reduction effect, increased material flow, and thermal effects (often neglected). Application to forging, coining, extruding, rolling, forming, and wire and tube drawing was described. Implications to the metalworking industries relate to reduced power requirements and extended capabilities of existing machines; reduced mean loads which permit greater area reduction per pass and possibly eliminate some operations; reduced frictional forces which result in smoother surfaces, elimination of chatter, and extended tool life; and less stringent lubrication requirements.

15. Jones, J. B., "Ultrasonic Metal Deformation Processing." Proc. CIRP International Conf. on Manufacturing Technology, Ann Arbor, Mich., Sept. 25-28, 1967, p. 983-1006.

Facilitation of metal forming processes, such as forging, extrusion, rolling, and tube, rod, and wire drawing were said to have been demonstrated, in some cases only on a laboratory scale, but in a few instances with production equipment and techniques. New equipment developments promoting production application included solid-state frequency converters, high-power ceramic transducers, efficient coupling systems, and force-insensitive mounts. The development of ultrasonic tube, rod, and wire drawing equipment and associated problems were described. Further extension of such processes with appropriate development effort was projected.

16. Lehfeldt, E., "Influencing Metallic Friction Processes by Means of Sonics in the 20-kHz Region." Dissertation, Rheinisch-Westfalischen Technischen Hochschule, Aachen, Germany, Feb. 13, 1968. (In German)

The mechanism of ultrasonic reduction in internal and external friction during metal deformation was examined theoretically and through experimentation with ultrasonics superimposed on tension, compression, bending, and shear deformation. Practical application was discussed at length with reference to ultrasonic wire drawing, extrusion, and metal powder densification, and brief mention was made of ultrasonic tube drawing, stretch drawing (such as dimpling), rolling, and forging.

17. Gentzsch, G., "The Use of Ultrasonic Vibrations in Metal Forming Processes." Bänder Bleche, Vol. 9, June 1968, p. 354-363. (In German)

Discussion of theoretical principles of the effect of vibrations on the mechanical properties of metals was followed by a review of the effects of ultrasonics on internal and external friction. Ultrasonic applications in

wire drawing, tube drawing, rolling, forging and upsetting, deep drawing, and compacting of metal powders were described.

18. Severdenko, V. P., V. V. Klubovich, and A. V. Stepanenko, Ultrasonic Rolling and Drawing of Metals. Nauka i Tekhnika, Minsk, USSR, 1970. (Translation by E. H. Virden, Consultants Bureau, New York, 1972).

This comprehensive review of USSR work in metal deformation, presented against a background of world-wide development, covered all possible modes of ultrasonic activation and transmission into the deformation locale in rolling and drawing (tubes, rods, and wires) of metallic materials, and the results obtained in terms of force parameters, surface quality, and mechanical properties. Despite demonstrated engineering suitability and economy of such processes, they have not found widespread practical use, possibly because of absence of basic data on the physical principles involved.

Tube Drawing

19. Tarpley, W. B. and H. Kartluke, "Ultrasonic Tube Drawing: Niobium, Zircaloy-2, and Copper." Report NYO-10008, Aeroprojects Inc., AEC Contract AT(30-1)-1836, Dec. 1961.

Ultrasonic die activation at 20 kHz and power levels up to 1000 watts was applied during drawing and sinking of 1/4-in. copper, Zircaloy-2, and niobium tubing. Area reductions ranging from 12 to 75% were investigated at draw forces up to 2700 lb and drawing rates up to 2880 in./min. Rate increases ranged up to 13-fold for copper and 100-fold for Zircaloy-2. At constant rate, force reductions of 40-80% were obtained with copper and 15% with niobium. Tubing that could not ordinarily be drawn under a given set of conditions was effectively drawn with ultrasonic activation.

20. Boyd, C. A. and H. Kartluke, "Application of Ultrasonics in Tube Drawing." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 22-28.

Preliminary data obtained in ultrasonic tube drawing (Ref. 19) were reviewed. Theoretical analysis of the drawing tension required, both with and without ultrasonic activation, was presented as a function of cross-sectional area reduction and the maximum drawing ratio obtainable without breakage as a function of ultrasonic power input. Experimental data obtained with several materials showed reasonable agreement with theory. A general equation was evolved for predicting the ultrasonic effect on drawing tubing of a given material when the yield strength of the material is known.

Tube Drawing

21. Mainwaring, B., "Application of Ultrasonics to Tube Drawing." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 28-29.

Ultrasonic effects during production drawing of small-diameter tubing were described. In one application that normally required three draw passes, 1100-H16 aluminum tubing was ultrasonically drawn in two passes, with 50% area reduction in each pass, thus saving 25-30% machine time. Type 304 stainless steel tubing was ultrasonically drawn to 35-38% reduction at 35 ft/min. Advantages were stated to be elimination of chatter, increased area reduction per pass, reduced drawing force, improved surface finish, and minimized galling, resulting in extended tool life.

22. Verderevskii, V. A., V. N. Nosal', et al., "Reduction in the Drawing Stress of Metals in the Presence of Ultrasound." Ultrasonic Technology, TsINTIAM, Moscow, 1964, p. 18-21. (In Russian; cited in Ref. 18)

In drawing steel tubes with ultrasonic activation of the mandrel at 20 kHz and 0.003-mm amplitude and at a drawing rate of 1 cm/sec, theoretical data indicated that friction reduction should reduce draw force by 20-25%; experimental data indicated a reduction of 25-30%. The disagreement was explained by the fact that mandrel vibration was transmitted to the die and partially reduced friction between die and tube.

23. Nosal', V. V. and O. M. Rymsha, "Reduction of Draw Force and Determination of Technological Parameters in Ultrasonic Tube Drawing." Stal', 1966, No. 2, p. 581-585. (In Russian; cited in Ref. 18)

A production drawbench at the Moscow Tube Plant was equipped for longitudinal 20-kHz ultrasonic activation of the die. In drawing steel tubes at a rate of 0.4 m/min and vibratory amplitude of 0.001 mm, draw force dropped by about 35%. At 25 m/min and 0.004 mm, draw force reduction was about 20%. The effect was attributed entirely to decreased friction between die and tube.

24. "Ultrasonic Activation Aids Tube Production." Tooling and Production, Vol. 31, May 1966, p. 96.

Ultrasonically activated back support plugs in tube drawing reduced friction and increased plasticity. Production benefits included: increased area reduction per pass, better size control, improved ID surface finish, greater tool life, routine production of thin-wall tubing, ability to make complex shapes in one pass, minimized chatter, and reduced lubrication breakdown. Specific examples of ultrasonic benefits observed during development were discussed.

Tube Drawing

25. Severdenko, V. P. and Yu. N. Resnikov, "Heating of Tubes During Drawing in an Ultrasonic Field." Doklady Akademii Nauk BSSR, Vol. 10, No. 6, 1966, p. 388-390. (In Russian)

During non-mandrel drawing of 1.5-mm-diameter copper tubes with ultrasonic die activation, the tube temperature reached 350°-370°K at draw speeds of 100-150 mm/min. The heating effected a 2% decrease in ultimate tensile strength of the material.

26. Clauser, G. E., "Production Tube Drawing of Metals Using Ultrasonic Energy Applied to the Mandrel." Tech. Report C6-26.4, 1966 National Metals Congress, Chicago, Oct. 31-Nov. 3, 1966. Also "Ultrasonic Process Speeds Tube Drawing." Steel, Vol. 159, Nov. 14, 1966, p. 38.

Ultrasonic activation of the mandrel in fixed-plug tube drawing was found to increase draw speeds, increase area reduction per pass, increase mandrel life, and produce better surface finish, thinner walls, and tighter tolerances. The time required to cold-draw stainless steel tubing was reduced 35%; similar results were obtained with brass and aluminum tubing of 1/8 to 1/2 in. ID. Shaped tubing with inside corner radius of 0.004 in. was produced; this radius is limited to 0.015 in. in conventional drawing. The effect was attributed to reduced friction at the tube-mandrel interface.

27. Clement, J. and G. Clauser, "Ultrasonics Takes on Another Metal-Forming Job." Metalworking, Vol. 23, March 1967, p. 128-129.

Ultrasonic plug-activated tube drawing in actual production effected burnished ID, with surface finish routinely at 8 μin., virtual elimination of chatter and galling, improved tool life, increased area reduction per pass so that fewer passes and anneals were required, and fabrication of complex shapes in a single pass. The key to production use was said to be the force-insensitive mount, which essentially eliminated frequency shifts and energy losses. Specific examples of benefits obtained in production drawing various tubing materials, and the setup and use of production equipment, were described.

28. "Tube Drawing Via Ultrasonics." Iron Age, Vol. 200, July 6, 1967, p. 65.

Ultrasonic cold drawing of tubing was being effectively used in production to improve surface finish, give faster drawing speeds and up to 50% greater area reduction per pass than otherwise possible. Draw force was reduced 5 to 10% and back tensions on the plug 20 to 40%. Chatter was almost wholly eliminated. The effects were observed with stainless steels, nickel alloys, beryllium-copper, brass, copper, aluminum, zirconium, and palladium-silver. Material and labor costs were reduced and rejections were fewer.

Tube Drawing

29. "Ultrasonics Make Big Impact on Tube Drawing." Metalworking Production, Vol. 111, Aug. 9, 1967, p. 50.

Ultrasonic tube drawing was stated to be a major technological advance, with the advantage that the ultrasonic plug drawing systems can be installed on most existing drawing equipment without major modifications. Increased tool life was obtained because of reduced friction; draw force was reduced by 5 to 10%; ID surface finish of 7 μin. was obtained; and tube production was increased by 35%.

30. Jones, J. B., "Ultrasonic Metal Deformation Processing." Proc. CIRP International Conf. on Manufacturing Technology, Ann Arbor, Mich. Sept. 25-28, 1967, p. 983-1006.

Tube drawing was said to be the only ultrasonic deformation process to date in which production application had been achieved. It had proved economically feasible, effecting significant time and cost savings, and technically desirable, producing a superior product or permitting the drawing of cross-sectional shapes not otherwise possible. Benefits included increased drawing rate with virtual elimination of stick-slip, chatter, and lubricant breakdown, and an associated tool life extension; decrease in draw force and tensile fracture avoidance; and increased area reduction per pass, so that fewer passes were required to achieve a given end geometry. Greatest production benefits were noted in the areas of thin-wall and shaped tubing, with the required smooth surfaces, close tolerances, and sharp inside corner radii.

31. Ahlquist, H. B., "Cold Drawing Larger Diameter Ferrous Tubing Using Ultrasonics." 1967 AIME Operating Metallurgy Conf., Chicago, Dec. 11-15, 1967.

Ultrasonics was said to bring to the tubing industry the first major tube drawing change in over 70 years. Using a 15-kHz plug-drive system, area reductions were increased by 20-50%; drawing rate was increased from 90 to 135 ft/min; chatter was almost entirely eliminated; tool life was extended through reduction of friction; and surface finish was substantially improved. One lot of tubing that normally required 5 manufacturing cycles was processed in 3 cycles. Production advantages included reduced material and labor costs, fewer rejections, and greater productivity.

32. Jones, J. B., "Tube Drawing, Draw Ironing, Flare and Flange Forming." Metal Progress, Vol. 93, May 1968, p. 103-107.

The development of ultrasonic tube drawing and its production use were described, with emphasis on tailoring the equipment and techniques to the specific application. Initially used for fixed-plug drawing on a drawbench,

often to replace moving-mandrel drawing, the process was later extended to floating-plug draw-block drawing wherein the die rather than the plug was ultrasonically excited. Typical applications and results were described.

33. "Ultrasonic Tube Drawing Enters Its Second Generation." Machinery, Vol. 74, May 1968, p. 88-89.

Second generation ultrasonic tube drawing equipment included a solid-state generator and ceramic transducers which increased power conversion efficiency to 75%. Productivity was increased by using two ultrasonic support-rod plug assemblies so that an operator could load a tube at one station while the other was drawing. Results included 36% reduction in production time, improvement in surface finish from 24 to 8 µin., and closely held tolerances, as well as the capability of producing shaped tubing with 0.004-in. corner radius.

34. Severdenko. V. P. and Yu. N. Resnikov, "Study of the Effect of Ultrasonic Oscillations on the Force of Drawing Tubes." Doklady Akademii Nauk BSSR, Vol. 12, No. 10, 1968, p. 999-1002. (In Russian; cited in Ref. 18)

Experiments in ultrasonic die activation during tube drawing established an optimum ultrasonic intensity beyond which the process became unstable and material damage could occur. This optimum varied with workpiece material and size. The optimum die angle for ultrasonic drawing was found to be in the range of 10-20 degrees. Draw force reduction under ultrasonic influence was 30-40% for copper tubes and 23-40% for brass tubes.

35. Nielsen, J. H., "Tube Drawing with Ultrasonics." ASTME Student Quarterly, Spring 1969, p. 17-19.

Use of ultrasonics in tube drawing demonstrated a number of advantages over conventional plug or rod drawing. Traditionally, rod drawing was used in production of thin-wall tubing, but separation of rod and tube after drawing caused major problems in dimensional control. With ultrasonics, plug drawing could be utilized with good dimensional control. Faster drawing rates, reduced force, greater area reduction per pass, longer tool life, smoother ID surfaces, elimination of chatter, galling and lubricant breakdown, and production of thin-wall or shaped tubing were possible. The process was effectively used with stainless steel tubes up to 2.25-in. diameter.

36. Buckley, J. T. and M. K. Freeman, "Ultrasonic Tube Drawing." Ultrasonics, Vol. 8, July 1970, p. 152-158.

This review presented the design philosophy behind two different types of ultrasonic tube drawing equipment: plug-drive and die-drive systems. Current

commercial, industrial applications were emphasized. Standard plug-drive equipment was noted to be available at ratings up to 6.5 acoustical kilowatts for tubes up to 2.5-in. OD and 0.25-in. wall thickness; die-drive equipment of up to 5-kw capacity was available. Ultrasonics was said to provide the avenue for processing tubing to stringent design specifications.

37. Sugahara, T., T. Mochizuki, H. Tsuji, M. Ueki, I. Komine, and S. Fujiware, "Application of Ultrasonic Vibration to Metal Tube Drawing Process." Nippon Kokan Technical Report--Overseas, Dec. 1970, p. 51-59; June 1971, p. 27-36.

Industrial-scale experiments in 20-kHz ultrasonic plug-activated tube drawing at area reductions in the range of 18-50% and draw speeds up to 24 m/min showed force reductions on the plug in the range of 50-90% and on the die by 10-30%. Various plug designs and lubricants were investigated. The ultrasonic effect was attributed to reduced friction at the plug. With sufficient vibratory amplitude, chatter was eliminated. The results suggested the application of ultrasonics in drawing complex shapes.

38. Severdenko, V. P. et al., "Ultrasonic Metal-Drawing Programs." Vestsi Akademii Navuk BSSR, Seryya Fizika-Tekhnichnyk Navuk, 1971, No. 1. (Translation: Russian Ultrasonics, Vol. 1, April 1971, p. 92-95)

Brass tubes of 16 mm diameter were drawn with ultrasonic activation of the mandrel at rates of 0.05-0.40 m/sec and at an area reduction of 23.4%. With longitudinal vibration, the draw force was reduced up to 60%. With transverse vibration, the maximum reduction was 42%. Best results were obtained when the draw die was located at a stress antinode.

39. Drăgan, O. and E. Segal, "Regarding Contact Friction at the Deformation Focal Point During Cold-Drawing of Tubes on an Ultrasonically Activated Plug." Metalurgia (Bucharest), Vol. 24, No. 7, 1972, p. 469-471. (In Rumanian)

The influence of major technological parameters on contact friction in tube drawing with a plug activated with longitudinal ultrasonic vibration was investigated. The friction coefficient decreased with increase in vibratory amplitude and increase in draw speed. Theoretically calculated data were confirmed by experimentation.

Tube Drawing

40. Kolpashnikov, A. I., V. I. Sabushkin, and E. V. Molodchinin, "Drawing of Aluminum Alloy Tubes Under the Action of Ultrasound." Tsvetnye Metally, 1972, No. 4. (Translation: Russian Ultrasonics, Vol. 2, Oct. 1972, p. 196-200)

Drawing of aluminum alloy tubes was carried out with ultrasonic activation of the mandrel at 15-30 kHz and 1.5-kw power input into magnetostrictive transducers, and at drawing rates up to 300 mm/min. Draw force reductions ranged up to 25% and averaged about 18%. With too large an amplitude, the metal tended to stick to the tool, apparently because of a sharp temperature rise in the deformation zone. Ultrasonically drawn tubes showed a slight decrease in strength and increase in elongation over those drawn without ultrasonics.

Wire and Rod Drawing

41. Severdenko, V. P. and V. V. Klubovich, "Drawing of Copper Wire in an Ultrasonic Field." Doklady Akademii Nauk BSSR, Vol. 7, No. 2, 1963, p. 95-98. (Translation: Scientific Literature Consultants, Philadelphia)

Annealed and pickled copper wire, 1.57-mm diameter, was drawn with longitudinal ultrasonic die activation at 23 kHz and 0.012-0.020 mm amplitude, at drawing rates up to 500 mm/min, and at 36.5% area reduction. Initially the wire repeatedly broke in the location of a vibratory node; the breakage was eliminated by installing damping blocks at fixed distances on either side of the die. Draw force was reduced by 50% under ultrasonic influence, regardless of drawing rate. Strength and hardness were reduced by about 15% and elongation increased by about 15%.

42. Robinson, A. T., J. C. Connelly, and L. M. Stayton, "The Application of Ultrasonics to Wire Drawing." U. S. Naval Ordnance Test Station, China Lake, Cal.: Tech. Prog. Report 328, NOTS TP 3297, July 1963; Tech. Prog. Report 345, NOTS TP 3405, Nov. 1963; Tech. Prog. Report 352, NOTS TP 3463, Feb. 1964; Tech. Prog. Report 364, NOTS TP 3542, April 1964; Tech. Prog. Report 375, NOTS TP 3636, Aug. 1964. Also Robinson, "Application of Ultrasonics to Wire Drawing." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio Aug. 16, 1963, p. 10-13.

An ultrasonic wire drawing array was assembled using a 20-kHz ceramic transducer and titanium horn mounted on an engine lathe modified to operate as a drawbench. The wire passed through a hole in the transducer-coupling, which was mounted at a theoretical nodal point. Two isolators were later added to provide a constant length of wire and eliminate standing-wave effects. In drawing aluminum, copper, steel, and other materials, considerable

difficulty was encountered with metal buildup in the die throat and even welding of the wire to the die; this was alleviated with some materials by pickling in dilute acid solution. Heating of the wire was a problem with short wire lengths.

43. Boyd, C. A. and N. Maropis, "Application of Ultrasonics to Wire Drawing." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 13-22.

Data were presented showing effects of ultrasonic die activation at various power levels on draw tension during drawing of tin alloy and copper wire. The greatest effect was obtained at high ratios of ultrasonic power to draw speed. For example, at a speed of 100 ft/min, draw tension was reduced by 1/2 to 2/3 at power levels in the range of 60-200 watts to the transducer. A phenomenological theory was evolved to account for draw tension reduction in terms of reduced interfacial friction and/or increased plasticity, and to explain the decrease in force reduction with increasing velocity. Experimental data showed reasonable agreement with the theory.

44. Maropis, N., J. Devine, and C. A. Boyd, "Development of Ultrasonic Wire Drawing Equipment for Production Use." Research Report 63-74, Aeroprojects Inc., Dec. 1963.

Substantial force reductions were obtained in drawing small-diameter (0.010-in.) copper and tin alloy wire at rates up to 350 ft/min and ultrasonic power levels of 20-50 watts. Wire could be drawn ultrasonically at force levels where no drawing was possible without ultrasonics, and the wire often broke instantaneously when ultrasonics was discontinued during drawing. No frequency effect was noted in the range of 15-60 kHz. A six-element ultrasonic array was developed for activation of six consecutive draw dies for drawing fine wires to 0.003-in. diameter. Force reductions ranged from over 50% at drawing rates of 25-50 ft/min to about 10% at 750-1000 ft/min.

45. Langenecker, B., C. W. Fountain, and V. O. Jones, "Ultrasonics: An Aid to Metal Forming." Metal Progress, Vol. 85, April 1964, p. 97-101.

Low-stress yielding of metals under ultrasonic influence was illustrated by wire drawing with a longitudinally activated die located at a vibratory antinode. In the drawing of copper, mild steel, stainless steel, and tungsten wire of 0.05-in. diameter, draw forces were reduced up to 50%.

Wire and Rod Drawing

46. Robinson, A. T., "The Application of Ultrasonic Energy to Metal Wire Drawing." Wire and Wire Products, Vol. 39, Dec. 1964, p. 1925-1929, 1978-1979.

Ultrasonic wire drawing was carried out on a modified engine lathe that provided for draw speeds of 0.036 to 2.0 in./sec and incorporated a 20-kHz ceramic transducer and titanium stepped horn through which the wire was drawn. Copper, iron, aluminum, and stainless steel wires 0.040 to 0.072-in. diameter were ultrasonically drawn with substantially reduced draw forces. The load-time curve showed periodic fluctuations related to the wave length and draw speed; this condition was alleviated with an isolator located at a fixed distance from the die. With some materials, die pickup was a problem that was alleviated through surface preparation and efficient lubrication.

47. Robinson, A. T., J. C. Connelly, and L. M. Stayton, "The Application of Ultrasonics to Wire Drawing." U. S. Naval Ordnance Test Station, China Lake, Cal.: Tech. Prog. Report 382, NOTS TP 3675, Nov. 1964; Tech. Prog. Report 390, NOTS TP 3768, March 1965; Tech. Prog. Report 399, NOTS TP 3836, May 1965.

In continuation of the work of Ref. 42, a new ultrasonic wire drawing array, permitting draw rates up to 700 ft/min, was assembled. Preliminary evaluation showed that earlier problems had been essentially solved. Evaluation of copper, iron, and titanium wire indicated less workhardening under ultrasonic influence. Wire temperature increased to 105°F without and 180°F with ultrasonics. Copper wire ultrasonically drawn to 38% reduction at rates up to 243 ft/min and ultrasonic powers up to 150 watts showed draw load decreases up to 26%. The effect was dependent on ultrasonic energy density delivered to the wire and essentially independent of draw speed, except that higher power was required to achieve equivalent energy density at the higher speeds.

48. Vienna University, Physical Institute, "Investigation of the Effects of Ultrasonics on the Deformation Characteristics of Metals." U. S. Govt. European Research Contracts Program, Contract N 62558-3436, Final Report, Feb. 1, 1964 to Jan. 31, 1965.

Ultrasonic (20 kHz) wire drawing was carried out with the direction of vibration normal to the drawing direction and with the die located in a stress antinode. With several materials drawn at area reductions up to 21%, draw force was reduced by up to 62%, the effect being greater at larger displacement amplitudes. Lead wire could be reduced by 37% with ultrasonic and only 14% without ultrasonics. With some materials, ultrasonics effected no change in physical properties, but a slight increase in strength and microhardness occurred with aluminum alloys and a decrease with copper. After recrystallization, the structure of the ultrasonically drawn wire was more homogeneous and finer grained.

Wire and Rod Drawing

49. Olsen, K. M., R. F. Jack, and E. O. Fuchs, "Wire Drawing in Ultrasonically Agitated Liquid Lubricants." Wire and Wire Products, Vol. 40, Oct. 1965, p. 1563, 1566-1568, 1637. Also "Wire Drawing Technique Uses Ultrasonics to Obtain Smooth Surfaces." Light Metal Age, Vol. 23, Oct. 1965, p. 14.

Ultrasonic wire drawing was carried out with the die immersed in liquid lubricant to clean the wire before it entered the die and prevent accumulation of foreign matter in the die cavity. A multi-die system was assembled incorporating six 150-watt, 25-kHz transducers. Copper, aluminum, and nickel alloy wire were successfully drawn to 0.0015-in. diameter or smaller at area reductions up to 35% and rates up to 1000 feet per minute. Good dimensional uniformity was obtained.

50. Kralik, G., "The X-Ray Diffraction Patterns of Wire Drawn in an Ultrasonic Field." Acta Physica Austriaca, Vol. 20, 1965, p. 370-375. (In German)

Copper and aluminum wire of 3-mm diameter was ultrasonically drawn at 20 kHz in seven passes to 1.13 mm. With the die located at a vibratory node and the direction of vibration normal to the direction of the draw, the rotational symmetry of the x-ray diffraction pattern was suppressed, and the results suggested promotion of twinning with ultrasonics.

51. Oelschlagel, D. and B. Weiss, "Ultrasonic Facilitation of Wire Drawing." Acta Physica Austriaca, Vol. 20, 1965, p. 363-369. (In German) Also Oelschlagel and Weiss, "Improved Efficiency in Wire Drawing with Ultrasound." Transactions of the ASM, Vol. 59, 1966, p. 685-693. (In English)

Ultrasonic wire drawing was carried out with the draw die located at a pressure antinode of a standing wave and at a rate of 3 cm/min. Draw force reductions ranged up to 37% for aluminum, 48% for iron, and 62% for lead. Cross-sectional reduction was also greater with ultrasonics: 37% for lead compared to 14% without ultrasonics. It was not determined to what extent the effect was attributable to friction reduction or to the softening effect of ultrasonics.

52. Vienna University, Physical Institute, "Investigation of the Effects of Ultrasonics on the Deformation Characteristics of Metals." U. S. Govt. European Research Contracts Program, Contract N 62558-3436, Final Report, Feb. 1, 1965 to Jan. 31, 1966.

Subsequent to work described in Ref. 48, investigation was made of the significance of several parameters in ultrasonic copper wire drawing. The effect on force reduction decreased with increasing draw speed and became essentially zero above about 20 m/min. There was a linear increase in the effect with increase in ultrasonic intensity. Increase in area reduction

from 15 to 33% led to a slight decrease in drawing facilitation. A die angle of about 14 degrees appeared to be most advantageous.

53. Stayton, L. M., G. A. Hayes, J. C. Connelly, and A. T. Robinson, "The Application of Ultrasonic Energy to Metal Wire Drawing." NOTS TP 4170, U. S. Naval Ordnance Test Station, China Lake, Cal., Oct. 1966.

Duplication of copper wire drawing experiments described in Ref. 47 showed divergent results. Parasitic frequencies apparently were self-induced in the ultrasonic system, and effects on draw load were variable. After equipment adjustments, including variations in horn design, the energy density effect on draw load was again demonstrated, with extreme precision in control of the variables. The equipment was reworked to permit drawing fine tungsten wire at 900°F. Although some draw force reduction was demonstrated, technical problems associated with the high temperature limited success. Further cold drawing of fine copper wire (tin-coated) showed load reductions up to 65% and confirmed reduced work-hardening with ultrasonically drawn wires.

54. Pohlman, R. and E. Lehfeldt, "Influence of Ultrasonic Vibration on Metallic Friction." Ultrasonics, Vol. 4, Oct. 1966, p. 178-185.

After experimental studies to verify the ultrasonic effect in reducing friction, wire drawing was carried out with 21-kHz longitudinal ultrasonic excitation of the die mounted at a vibratory node. Copper and aluminum wire was drawn at a rate of 100 mm/min and cross-sectional reduction of 18%. During drawing, the draw force varied periodically at distances equal to 1/2 wavelength; this effect was minimized by placing a second die at a fixed distance from the first. Draw force was reduced by 50% with copper and 30% with aluminum. The effect increased with increasing ultrasonic power and decreased with increasing draw rate, and was attributed to reduction in both internal and external friction.

55. Maropis, N., "The Application of Vibrational Energy to the Drawing of Metallic Materials." Report AFML-TR-66-296, Aeroprojects Inc., Air Force Contract AF 33(615)-2169, Nov. 1966.

Ultrasonic energy in longitudinal and radial modes at 7, 15, and 28 kHz was applied to drawing of titanium, aluminum, and steel rods at area reductions up to 37%, drawing rates up to 200 ft/min, and power levels up to 8 kw. Draw force reductions ranged up to 30% and higher; smooth drawing was obtained where it was not possible without ultrasonics. Surface finish of the drawn rods was improved, strength and ductility of the steel rods were increased, and no effect on metallurgical structure or microhardness could be detected.

Wire and Rod Drawing

56. Maropis, N., "The Application of Vibrational Energy to the Drawing of Metallic Materials." Report AFML-TR-66-296, Aeroprojects Inc., Air Force Contract AF 33(615)-2169, Nov. 1966.

Ultrasonic drawing of soft copper and hard steel wire was carried out at 28 kHz and 60 kHz, with axial and torsional die activation, and at rates up to 1000 ft/min. The lower frequency was more effective because of the greater vibratory amplitude obtainable, and the axial mode was more effective than the torsional. Significant draw force reductions were obtained under all conditions, but the effect decreased with increasing drawing rates. Using a back-tension technique, efforts to separate the friction effect from the redundant deformation effect of ultrasonics provided no quantitative data but indicated the primary effect to be friction reduction, with increased deformability of the wire occurring only at the higher energy levels.

57. Severdenko, V. P., K. V. Gorov, Ye. G. Konovalov, V. I. Yefremov, and L. A. Shevchuk, Ultrasound Treatment of Metals. USSR, 1966. (Air Force Translation FTD-MT-24-439-68)

Drawing of annealed 1.57-mm-diameter copper wire was carried out with 23.5-kHz axial activation of the die at draw speeds up to 500 mm/min. Wire breakage at 1/4-wavelengths along the wire was minimized by damping blocks placed on either side of the die. The ultrasonic vibration decreased draw forces by 50%, decreased wire tensile strength by 15%, and increased elongation by 40%. The effects were attributed to reduction of external friction and reduction of resistance to deformation.

58. Weiss, V., "Investigation of Phenomenon of Superplasticity in Metals." Syracuse University, Navy Contract N00019-67-C-0232, Quarterly Prog. Report No. 1, April 14, 1967.

In an investigation of the effects of superplasticity and ultrasonics, 1/8-in. diameter wire was drawn to 10-20% area reduction through a die activated at 20 kHz at power inputs up to 38 watts. Several types of steel, nickel, brass, and aluminum alloys were investigated at rates of 1-2 in./min. Load reductions ranged up to 30%, but in some instances after initial decrease, the load increased to a level higher than required without ultrasonics, possibly because of extraneous vibrations in the wire or because of loose couplings in the system.

59. Robinson, A. T., G. A. Hayes, J. C. Connelly, and L. M. Stayton, "The Application of Ultrasonic Energy to Metal Wire Drawing." NOTS TP 4416, U. S. Naval Ordnance Station, China Lake, Cal., June 1967.

Ultrasonic wire drawing experiments with variation in die position showed the draw load to be minimum when the die was located at the end of

the horn in a displacement antinode. Efforts to draw through a die excited to radial vibration were thwarted by progressive failure of the bolt retaining the ceramic transducer wafers. The transducer assembly was redesigned to correct this difficulty. Plans were made to conduct x-ray diffraction studies for further evaluation of plastic flow phenomena in wire drawing.

60. Robinson, A. T., J. C. Connelly, L. M. Stayton, and G. A. Hayes, "Study of the Application of Ultrasonic Energy to Wire Drawing of Metals." First Quarterly Prog. Report, U. S. Naval Weapons Center, China Lake, Cal., Oct. 1, 1967.

New aerospace and aircraft applications call for titanium wire of close tolerances, uniform thin cross sections, and smooth surface finish. This study investigated possibilities of ultrasonic wire drawing to meet these needs. A back-tension device and a capstan of steeper taper were designed and fabricated, and dies contoured specifically for titanium were used. Problems of breakage in tension were discovered to be caused by surface defects in the wire probably induced during previous draws at the mill. Ultrasonic influence was found to reduce drawing load.

61. Kevern, J., "Ultrasonics: Intense Energy with a Delicate Touch." Product Engineering, Vol. 39, April 22, 1968, p. 103-110.

In work carried out at Bell Laboratories (see Ref. 49), in which wire is drawn through dies submerged in an ultrasonically agitated liquid, copper and hard nickel-chrome alloys were drawn to 0.0007 in. diameter. Pure copper was drawn from 0.01 in. to 0.003 in. at 1000 ft/min with nine dies, each producing 30% cross-sectional area reduction; conventional drawing would reduce the wire only 20% per die and would require 14 dies. Aluminum wire as fine as 0.003-in. diameter was successfully produced.

62. Maropis, N., H. Edelson, and F. R. Meyer, "Ultrasonic Drawing of Fine Beryllium Wire." Research Report 68-32, Aeroprojects Inc., May 1968.

Unclad beryllium wire of 0.005-in. diameter was reduced to 0.001 in. by ultrasonic warm drawing at a temperature of 250°C in successive passes at about 12.5% area reduction per pass, and at drawing rates from 320 ft/min for the larger wires to 100 ft/min for the finer wire. With ultrasonic cold drawing, the 0.005-in. wire was reduced to 0.0039 in. without interdraw annealing. After three further cycles of annealing and drawing, the wire was reduced to 0.00229 in. The wire produced by both methods showed good tensile strength (180,000-200,000 psi), which apparently was limited by large foreign particle inclusions in the wire, often as large as 1/3 the wire diameter. The work was carried out with 28-kHz longitudinal vibration of the die at power levels up to 200 watts input to the transducers.

Wire and Rod Drawing

63. Pohlman, R. and E. Lehfeldt, "Wire Drawing with Superimposed Ultrasonic Vibrations." Draht, Vol. 19, Oct. 1968, p. 757-765. (In German)

Wire of copper, steel, brass, aluminum, and other materials was ultrasonically drawn with longitudinal and transverse die oscillation at 21 kHz and up to 400 watts power. Reduction per pass was about 15% and draw speed was 100-200 mm/sec. With both vibratory modes, draw force reductions of 9-50% were obtained, depending on the vibratory amplitude and drawing speed. No effect was obtained above 200 m/sec. From an analysis of the stresses, the authors concluded that the draw force decrease was due to the superposition of vibratory stresses on the drawing stresses rather than a reduction in contact friction.

64. Inoue, M. and E. Mori, "Ultrasonic Metal Wire Drawing." Reports of the 6th International Congress on Acoustics, Tokyo, 1968, p. 21-28. (Cited in Ref. 18)

Investigations were made of the ultrasonic effects on wire drawing with the draw die located at a stress antinode and at a motion antinode; also with the direction of vibration both axial and normal to the draw direction. Both vibratory modes produced substantial decrease in draw force. With steel wire at 10-20% area reduction, force reductions ranged from 20 to 50% at 60 mm/min and from 9 tc 14% at 60 m/min. Similar results were obtained with nichrome and copper wire. With regard to die location, the stress antinode was more effective but caused significant heating of the die and the wire. The force reduction was attributed to the addition of alternating stresses to static stresses.

65. Winsper, C. E. and D. H. Sansome, "Fundamentals of 'Ultrasonic' Wire Drawing." Journal of the Institute of Metals, Vol. 97, Sept. 1969, p. 274-280.

In longitudinal ultrasonic wire drawing at 20 kHz, an optimum die-to-drum distance was determined to be a multiple of 1/2 wavelength. Experimentation indicated force reduction to be directly proportional to vibratory amplitude and independent of area reduction. No increase in wire temperature occurred, and friction reduction was not considered significant. Force reduction was attributed entirely to a force superimposition mechanism. Analysis indicated reduced vibratory amplitude as speed was increased, and essentially zero force reduction when the mean drawing velocity equalled the peak velocity of die vibration.

66. Law, D., "Applying High Power Ultrasonics in the Wire Industry." Wire Industry, Vol. 36, Dec. 1969, p. 1055-1060. Also "Applications of High-Power Ultrasonics in the Wire Industry." Mass Production, Vol. 46, March 1970, p. 17-24.

In addition to ultrasonic cleaning, descaling, and plating of wire, ultrasonic wire drawing can be accomplished with vibrations applied either normal or axial to the direction of drawing. With either method, force reductions up to 65% have been observed, the effect being greatest at low drawing rates. Surface finish was improved and tensile strength reduced by as much as 15%. Wet drawing under ultrasonic influence was stated to provide cleaner, smoother wire and could be used at speeds up to 2000 ft/min.

67. Severdenko, V. P., V. V. Klubovich, L. K. Konyshev, and R. A. Repin, "Wire Drawing of High-Strainable Materials Involving Superposition of Longitudinal Ultrasonic Oscillations." Doklady Akademii Nauk BSSR, Vol. 14, No. 5, 1970, p. 415-418. (In Russian; cited in Ref. 18)

Ultrasonic wire drawing of titanium, molybdenum, manganese nickel, and stainless steel was carried out at area reductions of 9-33% and draw speeds of 20-150 mm/min. Draw force reductions ranged as high as 81%. The effect increased with increasing area reduction. The ultrasonically drawn wire demonstrated decreased strength and increased ductility, and metal deformation was more uniform. There was no apparent difference in surface quality of the drawn wire.

68. Severdenko, V. P., A. B. Stepanenko, and E. G. Sychev, "Ultrasound Effect on Plastic Deformation in a Vacuum." Doklady Akademii Nauk BSSR, Vol. 15, No. 3, 1971, p. 217-218. (Translation: Russian Ultrasonics, Vol. 1, April 1971, p. 72-74)

With conventional wire drawing in a vacuum, the friction coefficient was about twice as high as in air, and adhesion of the metal to the tool was a problem. With ultrasonic activation of the die at right angles to the direction of draw, the draw force with steel wire of 3-mm diameter was substantially reduced both in air and in vacuum, and no adhesion to the tool was observed.

69. Jones, J. B., N. Maropis, C. F. DePrisco, and J. G. Thomas, "Ultrasonic Energy Applied to the Aluminum Extrusion Cladding of Tubes." AEC Report DP-418, Aeroprojects Inc., Nov. 1959. Also Tarpley, W. B., "Application of Ultrasonic Energy to Extrusion," DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 29-31.

Ultrasonic extrusion experiments were carried out with separate 20-kHz ultrasonic activation of the die, the ram, and the container at power levels up to about 1000 watts. In extrusion of 1.25-in.-diameter lead billets at a ratio of 25:1 and temperature of 300°C, extrusion rate at constant force was increased by 100-300%, and extrusion force at constant rate was decreased by 16-28%. In extrusion of aluminum billets at 11:1 ratio and 525°C and at constant ram speed, force required to initiate extrusion decreased by 15-20%. When vibratory power was turned on during extrusion, force abruptly decreased by 10-25%, then rose again when power was turned off. These effects were substantiated in aluminum extrusion cladding of steel tubes. Extrusion force at constant rate was reduced from 52 to 44 tsi with ultrasonic activation, and rate at constant force was increased by 200-300%.

70. Tursunov, D. A., "Metal Extrusion in an Ultrasonic Field." Kuznecho-Shtompovochnoe Proizvodstvo, 1964, No. 5, p. 10-11. (In Russian)

Hot extrusion of brass and copper was facilitated by ultrasonic activation of the plunger at 18-25 kHz and power levels up to 2.5 kw. With ultrasonic extrusion of brass and copper slugs 10 mm in diameter, extrusion force reductions were 20-26% for copper and 37-48% for brass, the effect depending on the extrusion temperature. There were no detectable changes in the microstructure of the extruded metal.

71. Severdenko, V. P. and V. A. Labunov, Doklady Akademii Nauk BSSR, Vol. 9, No. 12, 1965. (In Russian; cited in Ref. 18)

Experiments in 20-kHz ultrasonic activation during reverse extrusion of aluminum were carried out to evaluate ultrasonic effects on effectiveness of 23 types of lubricants. In all instances, extrusion force was substantially reduced. Greatest effects were obtained with mineral oils and oleic acid, wherein force was reduced to 1/2 to 2/3 of its non-ultrasonic value.

72. Lehfeldt, E., "The Effect of Ultrasonic Vibrations on the Compacting of Metal Powders." Ultrasonics, Vol. 5, Oct. 1967, p. 219-223.

In ultrasonic extrusion of a mixture of iron powder and waterglass, used for coating welding electrodes, the force required to extrude the mixture at constant rate was reduced to about one-sixth of its non-ultrasonic value. The work was done with ultrasonic activation of the ram, but the die could also be vibrated.

Extrusion

73. Zalesskii, V. I. and Yu. I. Mischenkov, "Selection of the Vibration System for Extrusion in an Ultrasonic Field." Izvestiya Vysshikh Uchebnykh Zavedenii, Chernaya Metallurgiya, 1969, No. 1, p. 116-119. (Brutcher Translation 7961)

In extrusion with ultrasonic activation of the die located at a displacement antinode, the vibratory energy was absorbed in the workpiece, effects on contact friction on the container walls were insignificant, and extrusions fractured. These defects were overcome by locating the die in a displacement node so that the container was subjected to large-amplitude vibrations. Experiments with 15-mm diameter lead specimens at 192 kHz produced successful extrusions with greatly reduced friction and more uniform metal flow.

Rolling

74. McKaig, H. L., "Applications of Ultrasonics to Metal Forming and Rolling." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 33-36.

Ultrasonic activation of the roller during rolling of 3/4-in.-wide strips of X-8001 aluminum alloy, copper, and 4340 steel, under an applied load of 1000 lb, effected increased thickness reduction by factors of 3 to 5 over non-ultrasonic rolling. In flattening 1/8-in.-diameter zinc wire with a 1000-lb normal load, ultrasonic activation of the roller reduced the thickness to 0.0625 in., whereas reduction without ultrasonics was to 0.098 in.

75. Cunningham, J. W. and R. J. Lanyi, "Study of the Feasibility of Applying Ultrasonic Energy to the Rolling Process for Sheet Metals." Final Report, Navy Contract NOw64-0294-J, Westinghouse Electric Corp., Pittsburgh, Pa., March 15, 1965.

Ultrasonic application to sheet metal rolling was investigated with the view to obtaining reduced yield strength and friction, and thus reduced roll pressure. With ultrasonic vibration of sheet material at 18.25 kHz and power levels up to 3500 watts, significant load reduction was obtained only at axial displacement nodes, amounting to 6% with aluminum, 2.5% with copper, and 2% with steel. Further efforts were devoted to the design of a transducerized roll incorporating nickel ring laminations with a nominal frequency of 10 kHz. Significant load reduction occurred with lead but only about 5% with aluminum, the effect being attributed to friction reduction. Further effort was recommended to design a more effective vibratory roll.

Rolling

76. Cunningham, J. W. and G. R. Douglas, "Investigation of the Feasibility of Applying Ultrasonic Energy to the Rolling Process for Sheet Metals." Final Report, Navy Contract NOw65-0561-d, Westinghouse Research Labs., Pittsburgh, Pa., Sept. 1966.

To supplement the work of Ref. 75, four rolls containing piezoelectric or magnetostrictive transducers were constructed. Design parameters of the transducers were developed and various roll constructions investigated. Experiments proved the superiority of the piezoelectric design. Rolling load reductions of greater than 50% were achieved on aluminum and lead at light mill loads, but percent reduction became quite small at high mill loads. However, as the rolled material became thinner, the load reduction increased even at heavy loads, indicating that ultrasonics reduces friction loading and may prove beneficial in rolling thin-gage strip. The edge condition of aluminum foil was markedly improved by ultrasonic rolling.

77. Eidzi, M. and I. Masao, Bulletin of Japan Institute of Metals, Vol. 7, Jan. 1968, p. 27-33. (In Japanese; cited in Ref. 18)

Using a modified ultrasonic roller welder, experiments were carried out in flattening aluminum, copper, and steel wire of 0.6-1.98 mm diameter. At constant load, the amount of deformation increased with increasing vibratory amplitude. The ultrasonic effect decreased with increasing static load; this was attributed to disruption of the acoustic transmission system at the higher loads.

78. Severdenko, V. P., A. V. Stepanenko, and L. V. Zayash, "Rolling with Superimposed Ultrasonic Oscillations." Doklady Akademii Nauk BSSR, Vol. 12, No. 8, 1968, p. 693-698. (In Russian; cited in Ref. 18)

Rolling of aluminum, copper, and steel was carried out with longitudinal ultrasonic (19.6 kHz) oscillation of the rolls at 2.5 kw power and at a rate of 0.033 m/sec. Force reductions of 55% for aluminum, 32% for copper, and 21% for steel were obtained simultaneously with increased cross-sectional area reduction. The effects were attributed to the interaction of the coefficient of contact friction and the alternating tangential stresses.

79. Severdenko, V. P., A. V. Stepanenko, and H. G. Sychev, "Rolling with Radial Ultrasonic Vibration of Shafts." Doklady Akademii Nauk BSSR, Vol. 13, No. 9, 1969, p. 806-809. (In Russian; cited in Ref. 18)

Rolling of metal strips 3 mm wide was carried out with radial ultrasonic activation (19.2 kHz) of both contacting rolls in opposite phase. In reducing 0.5-mm-thick copper by 30%, force was reduced by 32% and rolling torque by 62%. With 50% reduction of aluminum, reductions of 70% in force and 85% in rolling torque were obtained. The ultrasonic effect was immediately apparent whenever the ultrasonics was turned on or off during rolling.

Rolling

80. Percival-Barker, K., "A New Design of 'Rolling Mill'." Sheet Metal Industries, Vol. 47, Oct. 1970, p. 894.

A new "rolling mill" design, developed in England, incorporated ultrasonic transducers and linear motors to effect thickness reduction. There were no actual rolls involved, and the process was actually one of ultrasonically facilitated extrusion. Reduction ratios as high as 14,000:1 were achieved in a single pass at production speeds up to 5000 ft/min. No descaling or interstage annealing was required. Costs of installation, operation, and maintenance were said to be substantially reduced over those of conventional rolling mills. Continuous operation was indicated to be feasible.

81. Konovalov, E. G. and E. P. Ignashev, "Flattening Round Wire into Microtape by Ultrasonic Oscillations." Doklady Akademii Nauk BSSR, Vol. 15, No. 11, 1971. (Translation: Russian Ultrasonics, Vol. 2, Jan. 1972, p. 49-54)

Production of microtape from wire on the basis of the known theory of rolling calls for expensive precision multi-high mills or special mills. The method reported here used only ultrasonic energy for the flattening. As the wire advanced between two dies (one attached to the ultrasonic transducer vibrating at 22 kHz), the deformation rate was high and little heating of the metal took place. This method was applicable to both soft and hard metals with a high degree of deformation and without lubrication. Transverse deformation by ultrasonic energy was generally greater than longitudinal deformation or deformation by rolling, and also greater for hard than for soft metals.

82. Severdenko, V. P., A. V. Stepanenko, and I. V. Zayash, "The Effect of Roll Velocity on the Efficiency of the Ultrasonic Oscillation Technique." Tsvetnaya Metallurgiya, 1972, No. 1. (Translation: Russian Ultrasonics, Vol. 2, Jan. 1972, p. 33-36)

It was shown theoretically that the amount of acoustical energy absorbed by the metal during ultrasonic rolling is proportional to the square of the vibratory amplitude and the length of the deformation zone, and inversely proportional to roll velocity. In the ultrasonic dry rolling of 0.5-mm-thick aluminum strip at velocities of 0.033 to 0.25 m/sec, load reduction was greatest at the higher compression ratios, and the effect of roll velocity was confirmed.

83. Ignatsev, E. P. and E. G. Konovalov, "Ultrasound Flattening of Refractory Metal Wires." Tsvetnaya Metallurgiya, 1972, No. 9, p. 73-74. (In Russian)

Experimental data were obtained on the flattening of molybdenum alloy wires to micro-ribbons by means of 21-kHz ultrasonic vibrations at an

amplitude of 0.015 mm. Considerable thickness reduction could thus be obtained without the use of lubricants and heating.

Forging

84. Severdenko, V. P. and V. V. Klubovich, "Investigation of the Microstructure of Copper Deformed in an Ultrasonic Field." Akademii Nauk BSSR, Fiziko-Tekhnichnyk Institut, Sbornik Nauchnykh Trudov, 1964, p. 124-128. (Air Force Translation FTD-TT-65-1408)

Ultrasonic upsetting at 22.5 kHz of copper samples 6 mm in diameter and 9 mm high was accomplished with 78% decrease in the stress normally required. With ordinary upsetting, the microhardness in the center of the specimen was maximum and the grains had a stretched form whereas surface grains were uniform. With ultrasonic upsetting, hardness was greatest on the surface and these grains showed the stretched form while those in the center were uniform. Overall hardness values were greater for the ultrasonic specimens.

85. Balamuth, L., "Progress in Ultrasonic Metal Forming." SAE Paper 971A, Automotive Engineering Congress, Detroit, Mich., Jan. 11-15, 1965.

Sufficient information was said to be available to permit design and fabrication of an ultrasonic forging machine for use in fabricating nose cones, automotive body sheet metal parts, and the like. Specifications were provided for a forging press operating at 30 kHz, 500 watts power, and 37.5 tons pressure. Comparison should be made of the operation of such a press with other forming methods.

86. Severdenko, V. P. and V. V. Klubovich, "Distribution of Deformation Along the Height of the Test Piece When Upsetting It Under Ultrasonic Vibrations." Izvestiya Vysshikh Uchebnykh Zavedenii, Chernaya Metallurgiya, 1965, No. 1, p. 61-64. (Brutcher Translation 6726)

Using a 23-kHz ultrasonic system incorporating a magnetostrictive transducer, copper and aluminum test pieces were upset within the range of 27 to 57% compression. Under normal conditions, deformation was greatest in the center of the specimen, while with ultrasonics the greatest deformation was on the contact surfaces. This ultrasonic effect became greater as intensity was increased. At 45% deformation, non-ultrasonic upsetting required 2000 kg, while ultrasonic deformation required only 800 kg.

Forging

87. Kristoffy, I. I., R. L. Kegg, R. R. Weber, "Influence of Vibrational Energy on Metalworking Processes." Report AFML-TR-65-211, Cincinnati Milling and Grinding Machines, Inc., Cincinnati, Ohio, Air Force Contract AF 33(657)-10821, July 1965. Also Kristoffy, "Metal Forming with Vibrated Tools." Journal of Engineering for Industry, Vol. 91, Nov. 1969, p. 1168-1174.

Ultrasonic forging of lead and aluminum alloy slugs and sleeves with 20-kHz axial activation of the punch resulted in apparent force reductions up to 60%, but addition of the dynamic peak force amplitude to the static force indicated no true force reduction. No material weakening effect was established. The type of force reduction was not affected by the workpiece material.

88. Balamuth, L., "Ultrasonics as Applied to Metal Forming and Assembly Processes." SAE Paper 650762, National Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, Oct. 4-8, 1965.

The ultrasonic effect on metals was examined in terms of thermal equivalence. To evaluate the effect of ultrasonic vs. static forming, small (1/8 and 1/4 in. square) aluminum slugs were deformed with and without 20-kHz vibration. The observed force decrease was considerably less than the dynamic force amplitude, indicating a clear softening effect. It was observed that such results should encourage the development of ultrasonic production equipment for such applications.

89. Izumi, O., K. Oyama, and Y. Suzuki, "On the Superimposing of Ultrasonic Vibrations During Compressive Deformation of Metals." Trans., Japan Institute of Metals, Vol. 7, No. 3, 1966, p. 158-167.

Samples of several metals and alloys were upset with and without ultrasonic activation at 22.5 kHz, with height reductions up to about 30%. Under ultrasonic influence the load required for a given deformation decreased with decrease in vibratory amplitude and in some instances was only 1/5 of that required for non-ultrasonic deformation. The effect was attributed primarily to lowering of flow stress, although heat generation was also a factor. Sensitivity to vibration differed with different types of materials.

90. Balamuth, L., "Ultrasonic Motors Fabricate Metals and Plastics." SAE Journal, Vol. 74, June 1966, p. 72-75.

The force required to cold-forge metal was substantially reduced when the punch was vibrated at ultrasonic frequency. When small slugs of aluminum were compressed by a punch vibrating at 20 kHz, static force drop was generally much greater than dynamic force, and the amount by which it exceeded the dynamic force increased with the dynamic force. Considerably greater static

force reductions should be obtainable with larger displacements, since more vibrational energy would be imparted to the piece.

91. Zhadan, V. T., "Influence of Ultrasonics on the Upsetting of Steels That Are Difficult to Work." Izvestiya Vysshikh Uchebnykh Zavedenii, Chernaya Metallurgiya, 1966, No. 11, p. 93-96. (Brutcher Translation 7062)

Experiments in upsetting heat-resistant steel specimens under 21-kHz vibratory influence showed reductions up to 15% in the force required to achieve a given deformation. The effect was attributed to the superposition of dynamic force on the static force, which promoted the movement of dislocations within the crystal structure and thus facilitated plastic deformation. The possibilities of using this effect in processing difficult-to-work materials were noted.

92. Severdenko, V. P., K. V. Gorov, Ye. G. Konovalov, V. I. Yefremov, and L. A. Shevchuk, Ultrasound Treatment of Metals. USSR, 1966. (Air Force Translation FTD-MT-24-439-68)

Ultrasonics (23.5 kHz) was applied to free upsetting of copper, aluminum, and steel cylindrical specimens 5-10 mm in diameter. Along the height axis, maximum deformation and greatest microhardness were found adjacent to the contact surfaces and minimums at the center with ultrasonic upsetting, whereas the reverse was true with non-ultrasonic upsetting. The latter produced a barrel-shaped specimen, while ultrasonically upset specimens had a reverse barrel shape. Required deformation load decreased with increasing ultrasonic intensity and approached zero at high powers.

93. Severdenko, V. P., V. V. Petrenko, and S. I. Petrenko, "Effect of Ultrasonic Vibrations on the Effectiveness of Lubricants During Free Compression of Aluminum." Vestsi Akademii Navuk BSSR, Seryya Fizika-Tekhnichnyk, Navuk, 1968, No. 2, p. 103-105. (In Russian)

Free compression of aluminum specimens 9 mm in diameter was carried out under ultrasonic influence to determine the effects achieved with several types of lubricants. Prior to compression, the specimens were soaked in the lubricants for 48 hours. In all cases, ultrasonics reduced the applied pressure required for a given degree of compression; in some instances, the effectiveness of the lubricant was increased by a factor of 4.5-6.5.

Forging

94. Severdenko, V. P. et al., "Change of External Friction by Free Upsetting of Steel in an Ultrasonic Field." Doklady Akademii Nauk BSSR, 1970, No. 6. (Translation: Russian Ultrasonics, Vol. 1, April 1971, p. 90-92)

The effect of ultrasonic vibrations on external friction in free upsetting of steel samples was established by plotting hardening curves according to Shofman's method and specific pressures. In upsetting with ultrasonic vibrations, external friction increased the specific pressure to a lesser extent, hence external friction was also less than in normal upsetting. The decrease of external friction in ultrasonic upsetting lowered resistance to deformation.

95. Severdenko, V. P. and V. V. Petrenko, "Effect of Plastic Deformation on Amplitude of Applied Ultrasonic Oscillation." Vestsi Akademii Navuk BSSR, Seryya Fizika-Tekhnichnyk Navuk, 1971, No. 1. (Translation: Russian Ultrasonics, Vol. 1, April 1971, p. 75-78)

Steel samples, 6-mm diameter by 9 mm high, were free-upset in a 5-ton stress tester fitted with a special die. After preliminary static loading, 19-kHz ultrasonic oscillations were applied. Plastic deformation was associated with monotone decrease of ultrasonic amplitude; in 27 sec after the onset of deformation, amplitude decreased by 5-7%. This was attributed to the fact that plastic deformation of metals changes their physico-mechanical strength properties, including internal friction which is amplitude-dependent and produces damping.

96. Abramov, O. V., V. I. Petukhov, and Yu. V. Manegin, "The Use of Ultrasound in Metal Forging." Tsvetnye Metally, 1971, No. 2, p. 64. (Translation: Russian Ultrasonics, Vol. 2, Jan. 1972, p. 17-22)

A system was developed to deliver ultrasonic vibration to the punch, die, or container in direct forging of aluminum, and to punch or reflector in reverse forging. Ultrasonic application reduced overall compression force and increased homogeneity of the material, the effect becoming greater with increased vibratory amplitude. With direct forging, the greatest effect was observed with die activation, with consequent lowering of surface friction forces. With reverse forging, activation of the punch was most effective.

Riveting

97. McKaig, H. L., "Application of Ultrasonics to Metal Forming and Rolling." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 33-36.

In upsetting aluminum rivets with a 1200-lb force without ultrasonics a 2.5% reduction of the head height was achieved. With 1200-watt ultrasonic power, reduction was increased to 14%.

98. McMaster, R. C., C. C. Libby, J. P. Mitchell, H. Minchenko, T. Burney, and W. White, "Sonically Assisted Deformation of Aluminum Alloys." Report 291-1, Dept. of Welding Engineering, Ohio State University, June 14, 1967.

Using a 10-kHz transducer assembly installed on a commercial riveter, riveting experiments were carried out primarily with 2024 aluminum alloy rivets, and also with 7075-T73 aluminum and titanium alloy rivets. Static forces for 5/16-in. rivets ranged from 200 to 250 lb, riveting times from 0.27 to 1.0 sec, and stack thickness from 0.25 to 0.50 in. Yield point tests showed strengths ranging from 1900 to 2790 lb, with 75% of the rivets falling within a 200-lb range. Instrumentation data indicated that repeatable data could be obtained using similar materials and rivet production procedures.

99. Delong, R. B., "Sonic Riveting." News in Engineering, Ohio State University, May 1968.

Experimentation in vibratory riveting was carried out using a 50-lb, 15-hp, 10-kHz electromechanical transducer with a 2600-volt power source. Good rivet upsetting was obtained with 1/4-inch-diameter titanium rivets in 1.5 sec and with 5/16-inch aluminum alloy rivets in about 1/2 sec under static force of 200 lb. Use of the transducer was said to allow major reductions in the size, strength, complexity, and cost of the supporting and positioning structure of riveters, permitting reduction in static force by 50 to 100 times. Portable riveters for field use appeared feasible.

100. Adcock, G., "Lockheed-Georgia Developing Ultrasonics for Riveting." Metalworking News, Dec. 23, 1968, p. 21.

Ultrasonic riveting was carried out using a 20-kHz magnetostrictive transducer and tapered horn, with a free-floating die mass to transfer the energy to the rivet. The energy was applied in 100 to 200 bursts per second providing peak stresses in the order of 140,000 lb. Deformation of the rivet was followed by bonding in the joint around the shank, giving the joint increased strength. Tensile-shear strength was almost double that of conventional riveted joints, and the bonding at head and tail provided a seal against corrosion. Though still in the development stage, the process was said to have potential for production application.

Riveting

101. Aeroprojects Inc., "Ultrasonic Riveting and Ultrasonic Drilling and Countersinking." Research Report 69-15, April 1969.

Upsetting of A-286 steel and 6Al-4V titanium rivets, carried out with 15-kHz activation of the riveting tool, effected force reductions of 35-60% with 1/8-in. rivets and 14-21% with 1/4-in. rivets. With equivalent force levels, the ultrasonically set rivets showed increased head diameter and improved shank expansion and hole fill. Results suggested the importance of controlling upset rate, dwell time, and ultrasonic pulse time. The process was said to be suitable for production, but further development was indicated, particularly to improve ultrasonic coupling into the rivet.

102. Libby, C. C., "Sonic Riveting of Aircraft Aluminum Alloys." IEEE Trans. on Sonics and Ultrasonics, Vol. SU-16, July 1969, p. 117-126.

The fundamental controlling factors and process parameters in sonic (10-kHz) riveting of aluminum were discussed. Results showed force reductions of as much as 100 to 1. The rivets showed no evidence of forging bursts, cracking, or splitting, and there was no indication of plate separation. Flow lines in the rivet were smooth, and the rivet was in contact with the joined plates throughout its entire length.

103. Aseff, G. V., W. H. Sproat, and A. Kremheller, "High-Intensity Ultrasonics." IEEE Trans. on Sonics and Ultrasonics, Vol. SU-17, Jan. 1970, p. 7-12.

Ultrasonic riveting experiments were carried out using a 20-kHz magnetostrictive transducer-coupling system with 1-kw power input. Rivets of 1/8-in. diameter were driven to join 0.063-in. 2024-T3 clad aluminum sheet in 1 to 8 sec. In addition to upsetting of the rivet heads, diffusion bonding occurred at the faying plane around the rivet shank and minor scattered bonding between the shank and the surrounding hole. Single-lap shear tests showed substantial strength increases for the ultrasonically driven rivets.

Stretch Forming

104. Peacock, J., "Forming Goes Ultrasonic." American Machinist, Vol. 105, Nov. 27, 1961, p. 83-85.

Dimples in titanium and aluminum alloy sheet up to 0.040 in. thick produced at room temperature using a ram vibrating at 14 kHz were at least as good as those obtained with a heated die. The titanium alloy showed greater elongation and ductility during squeezing, and friction was reduced. Difficulty was encountered because of damping of the vibrations under large static

forces, and it was suggested that future ultrasonic presses use two opposed rams vibrating 180° out of phase. It was considered feasible to adapt existing dimpling equipment for ultrasonic activation.

105. McKaig, H. L., "Applications of Ultrasonics to Metal Forming and Rolling." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 33-36.

In deep drawing of aluminum under a 1000-lb load, the depth achieved was increased by 37% when one die was activated with 600 watts ultrasonic power. In an effort to achieve the same depth without ultrasonics by increasing the load to 4000 lb, the formed part fractured, indicating improved formability under ultrasonic influence.

106. Langenecker, B., W. H. Frandsen, C. W. Fountain, S. R. Colberg, and J. A. M. Langenecker, "Effects of Ultrasound on Deformation Characteristics of Structural Metals." NavWeps Report 8482, NOTS TP 3447, U. S. Naval Ordnance Test Station, China Lake, Cal., March 1964. Also Langenecker, Fountain, and V. O. Jones, "Ultrasonics: An Aid to Metal Forming." Metal Progress, Vol. 85, April 1964, p. 97-101.

Copper cups were ironed and deep-drawn to approximately twice their original length using a 20-kHz ultrasonically activated punch. Forming stress was reduced to 70 lb from the 220 lb required for non-ultrasonic forming. Thus some intermediate steps in the usual ironing method may be eliminated. Likewise, lip curling under ultrasonic influence was accomplished with 50% reduction in forming forces. The effect was attributed to the apparent reduction in static yield stress, and possibly also to friction reduction.

107. Kristoffy, I. I., R. L. Kegg, and R. R. Weber, "Influence of Vibrational Energy on Metalworking Processes." Report AFML-TR-65-211, Cincinnati Milling and Grinding Machines, Inc., Cincinnati, Ohio, Air Force Contract AF 33(657)-10821, July 1965. Also Kristoffy, "Metal Forming with Vibrated Tools." Journal of Engineering for Industry, Vol. 91, Nov. 1969, p. 1168-1174.

Ultrasonic drawing and ironing of 4130 steel and 2024-T3 aluminum alloy blanks were carried out at 20 kHz and up to 2400 watts power, with axial vibration of the punch and/or radial vibration of the die. Apparent force reductions up to about 50% were achieved. These were attributed to replacement of a portion of the static force with dynamic force, frictional force reduction, and/or forming energy distribution change between the hydraulic press and the vibratory system. It was suggested that such ultrasonic application be used only where the same goals could not be accomplished by higher capacity conventional equipment. Surface finish of the formed parts was improved; there was no effect on hardness or microstructure.

108. Robinson, A. T., G. A. Hayes, J. C. Connelly, and L. M. Stayton, "The Application of Ultrasonic Energy to Metal Wire Drawing." NOTS TP 4416, U. S. Naval Ordnance Test Station, China Lake, Cal., June 1967.

An ultrasonic tool was used in spinning a tapered 1100-0 aluminum cup. Spun depth was increased from 3.30 to 3.55 in., cup cross section was more uniform, cracking was eliminated, higher hardness was achieved, and spring-back was eliminated, in comparison with non-ultrasonically drawn cups. No significant difference in microstructure was observed.

109. Jones, J. B., "Tube Drawing, Draw Ironing, Flare and Flange Forming." Metal Progress, Vol. 93, May 1968, p. 103-107.

Flaring of aluminum alloy, nickel alloy, and steel tubing without local annealing was accomplished with ultrasonic torsional vibration of the flaring tool. Static force was substantially reduced, cracking was eliminated, smoother surfaces and closer tolerances were achieved, and the physical properties of the material were not degraded. Flare angles ranged from 30° to 90°. This technique was successfully used to meet the extreme quality standards required for flared tubing connections for space vehicles.

110. Pruder, G. D. and J. G. Thomas, "Ultrasonic Draw Ironing of Aluminum Cartridge Cases." Research Report 68-10, Aeroprojects Inc., Army Contract DAAA25-67-C-0498, March 1968.

In the draw ironing of 7075 aluminum alloy cartridge cases, 15-kHz ultrasonic activation of either the punch or the die in the axial mode effected 30-40% reduction in the peak drawing force. Cases in the annealed and mildly heat-treated temper were ultrasonically drawn through two steps without intermediate anneal. Hard (T-6) cases were successfully drawn under conditions where non-ultrasonic drawing was impossible. The process offered the possibility of eliminating one draw pass, but this was not evaluated because suitable punches and dies were not available. Ultrasonic draw ironing was concluded to be practical for production use.

111. Aeroprojects Inc., "Ultrasonic Draw Ironing of Brass Cartridge Cases." Research Report 70-6R, Army Contract DAAA25-70-C-0008, March 1970.

Ultrasonic punch application during draw ironing of 5.56-mm brass cartridge cases from the initial to the final cup geometry permitted a three-draw process to be reduced to two draws and indicated the possibility of eliminating the intermediate anneal between passes. Chatter during drawing was eliminated, and up to 40% reduction in draw force was achieved. Ultrasonics appeared to have no effect on metallurgical structure or surface finish.

Stretch Forming

112. Rozner, A. G., "Effect of Ultrasound on Stresses During Strip Drawing." Report NOLTR 70-45, U. S. Naval Ordnance Lab., White Oak, Md., March 6, 1970. Also Rozner, "Effect of Ultrasonic Vibration on Coefficient of Friction During Strip Drawing." Journal of the Acoustical Society of America, Vol. 49, May 1971, p. 1368-1371.

Investigation was undertaken to determine the effect of ultrasonics on the stresses and the coefficient of friction during strip drawing, selected as a simple technological process involving two-dimensional strain. Specimens of copper, mild steel, and 70:30 brass, 3/4 in. wide, were drawn through a die mounted in an Instron testing machine and excited to 20-kHz vibration. In all cases ultrasonic application was accompanied by a sudden reduction in load and reduced coefficient of friction, the magnitude of the effect differing with different materials. The effect was explained by the superposition of oscillatory stresses on the drawing stress. The mechanical properties and microstructure of the drawn materials were unaffected.

Straightening

113. Konovalov, Ye. G., V. I. Yefremov, and V. K. Rimskiy, "Ultrasonic Removal of Stresses in Parts After Plastic Deformation." Ductility and Pressure Treatment of Metals, Nauka i Tekhnika, Minsk, USSR, 1964, p. 202-204. (Air Force Translation FTD-HT-23-894-68)

Ultrasonic treatment at 20 kHz through a water bath was used to stress-relieve reeling cylinders so that cylinder dimensions would remain constant after removing the enveloping ring. Non-treated specimens showed an average deviation of -0.078 mm, while those ultrasonically treated showed only -0.024 mm deviation from the nominal diameter of 52 mm. The effect was attributed to ultrasonic promotion of transition of a metal from a thermodynamically unstable to a more stable state by removing internal stresses.

114. Maropis, N., W. H. Bayles, J. Devine, and F. R. Meyer, "Ultrasonic Application to Facilitate Straightening of Steam Turbine Blades." Research Report 70-31, Aeroprojects Inc., Nov. 1970.

Ultrasonic progressive waves at 15 kHz were applied during bending and twisting of 1-inch-wide ribbons of 0.100- and 0.125-in.-thick 304 and 17-4 PH steels, using sufficient power to introduce dynamic stresses of 5000 psi. Each specimen was bent or twisted to a predetermined angle (up to 46°), subjected to ultrasonic pulses for 8 sec, then released. In every case, ultrasonics increased the permanent set of the material, i.e., springback was reduced. The effect was greatest at the lower bend or twist angles and greater with the 304 than the 17-4 PH steel. No effect on metallurgical properties was detected.

115. Freedman, A. H. and J. F. Wallace, "Improving the Properties of Engineering Metals by the Application of Ultrasonic Vibrations." Final Report, Case Institute of Technology, Cleveland, Ohio, Army Contract DAI-33-019-505-ORD-(P)-4, Aug. 1957.

Low-intensity (110 watts) 20-kHz vibrations were applied to compacting and sintering of powdered iron. An activated 7/8-in.-diameter punch in conjunction with a 20,000-lb load ffected a slight increase in density and hardness of green compacts, but it was noted that the system was force-sensitive. Experimental limitations in the sintering experiments resulted in considerable scatter in the data, and no conclusions could be drawn. Higher intensities were considered necessary to achieve significant effects.

116. Thomas, J. G. and J. B. Jones, "Application of Ultrasonic Vibration to the Compaction of Metal Powders." Report NYO-7921, Aeroprojects Inc., AEC Contract AT(30-1)-1836, June 1958.

Ultrasonic equipment for activating powdered metals during compaction was devised, utilizing force-insensitive mounting systems to permit operation at pressures up to 70 tons/in.^{2}. Vibration of the die in a bell mode proved more effective than axial or lateral vibration of the punch. Ultrasonic compaction of several metal powders, including hydrogen-reduced iron powder, produced significantly increased density. Mold fill was also facilitated by ultrasonic die activation, the powder density before pressing being increased by about 30%.

117. Tarpley, W. B., K. H. Yocom, and R. Pheasant, "Ultrasonic Extrusion: Reduction in Vehicle and Plasticizer Requirements for Non-Clay Ceramics." Report NYO-10006, Aeroprojects Inc., AEC Contract AT(30-1)-1836, Nov. 1961.

Ceramic and cermet powders mixed with plasticizer and water were extruded through a die ultrasonically activated at 20 kHz. Extrusion pressure was reduced as much as tenfold, and extrusion rate was increased several hundredfold. This technique permitted using only 40-60% of the amount of plasticizer and about 10% of the water used in standard commercial extrusion mixes, i.e., mixes too stiff for normal extrusion. The ultrasonically extruded specimens showed improved surface finish and increased green and as-fired density. Both hollow and solid objects of various geometries were successfully extruded.

118. Tarpley, W. B. and H. Kartluke, "Ultrasonic Hot Pressing of Metals and Ceramics." Report NYO-10007, Aeroprojects Inc., AEC Contract AT(30-1)-1836, Dec. 1961.

The feasibility of ultrasonic hot pressing was demonstrated, using a hermetically sealable, force-insensitive acoustic mounting system to penetrate

a high-pressure, high-temperature, controlled-atmosphere environment. The density of silver powder compacts was increased as much as 160% with ultrasonic activation. Under otherwise constant conditions, ultrasonics permitted substantial reductions in the temperature and/or pressure and/or time required to achieve equivalent densities. Similar results were obtained with ultrasonic hot pressing of calcium fluoride and submicron aluminum oxide powder.

119. Hochman, R. F. and R. M. Gray, "A Note on the Effect of Ultrasonic Activation on Diffusion and Sintering." International Journal of Powder Metallurgy, Vol. 2, 1966, p. 15. Also Hochman and Gray, "The Effect of Ultrasonic Energy on Diffusion and Sintering." Ultrasonics Symposium, Lockheed-Georgia Co., Marietta, Ga., Jan. 1966.

Ultrasonic effects on sintering and diffusion were examined in producing high-density sintered powder metal specimens of magnesium, aluminum, and lead. Sintering was accomplished during 18-kHz water immersion treatment of compacts retained in static compression. Compressive strength was increased by about 25% and tensile strength of lead by 37%. Related improvements were observed in the specific densities of these specimens.

120. Pokryshev, V. R. and V. I. Marchenko, "Method of Obtaining Compaction Products from Refractory Metallides Using Ultrasonic Activation." Poroshkovaya Metallurgiya, 1966, No. 8, p. 98-100. (NASA Tech. Translation F10,774)

A pressing and sintering apparatus, utilizing the combined and simultaneous action of static pressure and dynamic loads generated by an ultrasonic field, incorporated a magnetostrictive transducer and half-wave concentrator which delivered vibratory energy to the die, a resistance furnace capable of temperatures up to 2500°C, a vacuum chamber, and instrumentation for measuring operating variables. No data were provided; the device was proposed for use with metal and/or refractory powders.

121. Lehfeldt, E., "The Effect of Ultrasonic Vibrations on the Compacting of Metal Powders." Ultrasonics, Vol. 5, Oct. 1967, p. 219-223.

Several arrangements for ultrasonic compaction of metal powders, involving activation of the upper ram, were described. Experiments in cold pressing of nickel, aluminum, tin, and iron powders, with the tools mounted in a hydraulic press and activated at 20 kHz, showed increased density due to reduced interparticle friction and reduced wall friction, as well as increased strength and dimensional stability. Ultrasonic hot pressing resulted in higher densities at equivalent temperatures or equivalent density at lower temperatures.

Powder Metallurgy

122. Chachin, V. N. and G. K. Sadyako, "Effect of Ultrasonic Vibrations on the Process of Cermet Sintering." Soviet Powder Metallurgy and Metal Ceramics, 1968, No. 9, p. 693-694.

Compacted blanks of electrolytic copper powder, 20 mm in diameter and 6 mm high, were sintered at temperatures from 600 to 900°C for 30 minutes and subjected to 20-kHz ultrasonic application for 1-5 minutes. Shrinkage of the specimens was greater than that of non-ultrasonic controls by a factor of 1.5-2.0, and hardness was greater by 7%. The effect was attributed to reduced interparticle friction, rupture of oxide coatings, and increased plastic deformation of the particles.

123. Lehfeldt, E. and R. Pohlman, "Densification and Pressing of Metal Powders with Superimposed Ultrasonic Vibrations." Planseeberichte für Pulvermetallurgie, Vol. 16, 1968, p. 263-276. (In German)

In pressing iron powders in a mold with a punch ultrasonically activated at 20 kHz and with about 400 watts power, substantial increase in compacted density was obtained, particularly in the lower pressure range. The ultrasonically pressed powders were characterized by increased strength and homogeneity. The effects were attributed to reduced friction between the metal particles and reduced friction between the powder and the mold walls. In extruding metal powders mixed with binder and water with ultrasonic activation, extrusion pressure was reduced by a factor of six.

124. Pokryshev, V. R. and V. I. Marchenko, "Effect of Ultrasound Oscillations on the Consolidation of Iron Powder in Hot Pressing." Soviet Powder Metallurgy and Metal Ceramics, 1969, No. 2, p. 110-112.

Simultaneous hot pressing and vacuum sintering of iron powder was carried out at temperatures of 700-900°C with 22-kHz ultrasonic oscillation for 5 or 10 min either at the beginning or the end of the sintering process. The ultrasonically treated specimens showed substantial increases in density and hardness, and decrease in porosity. At the lower temperatures, ultrasonics exerted considerable influence on the initial stage and less on the later stage. At the higher temperature, the stage of application was less significant.

125. Drăgan, O. and A. Protopopescu, "Relationship between Density and Relative Height of Metal Powder Compacts Pressed under Ultrasonic Influence." Ultrasonics for Industry 1970, Conf. Papers, London, Oct. 20-21, 1970, p. 19-21.

In experiments in compaction of atomized iron powder with ultrasonic activation of the ram at 22 kHz, greater densification was obtained with the higher height-to-diameter ratios. For example, at h/d = 1, density was increased over that of non-ultrasonic samples by 6.51%; at h/d = 3, density was increased by 22.16%. The ultrasonic effect was attributed to particle rearrangement, removal of adsorbed gases on the surfaces of the particles, and heating of the compact from ultrasonic absorption.

Powder Metallurgy

126. Konovalov, E. G. and V. M. Zhdanovich, "Effect of Ultrasonic Oscillations on Compressibility of Metal Powders." Doklady Akademii Nauk BSSR, Vol. 15, No. 3, 1971, p. 219-221. (Translation: Russian Ultrasonics, Vol. 1, April 1971, p. 78-81)

It was shown experimentally and theoretically that the density of metal powders compacted under ultrasonic influence is proportional to residual porosity and amplitude, and inversely proportional to compression height. The equations developed permit determination of the magnitude of the static load applied under given conditions.

127. Kostin, L. G., L. T. Buchek, and V. M. Shkil', "Schemes of Ultrasonic Pressing of Powder Materials and Engineering Methods for Calculating the Acoustic System." Soviet Powder Metallurgy and Metal Ceramics, 1971, No. 4, p. 264-267.

Three principal schemes for transmitting vibrations to the pressing tool in ultrasonic pressing were recognized: longitudinal, transverse, and torsional tool vibration. In each, ultrasonic energy may be applied to the die, to the punch, or to both die and punch. Calculations were presented for the design of the simplest systems--longitudinal excitation of the die. The technique was said to make it possible to determine the geometric dimensions of the acoustic system and the pressing tool, to locate the displacement node of the acoustic concentrator, and to locate the pressing deformation zone in the region of maximum vibratory amplitude.

128. Pokryshev, V. P., M. S. Koval'chenko, and V. I. Marchenko, "Vacuum Hot Pressing of Metal Powders under the Action of Ultrasonics." Soviet Powder Metallurgy and Metal Ceramics, 1971, No. 10, p. 790-794.

Ultrasonic application at 21 kHz during vacuum hot pressing of iron and nickel powders, supplemented by theoretical considerations, indicated that ultrasonics applied at the beginning of compaction accelerates the propagation of transient processes but has no marked effect on steady-state creep. Applied at the second stage, ultrasonics affects the creep process by increasing its rate. Density of the sintered specimens was increased with ultrasonics; this effect decreased with rise in temperature.

129. Pokryshev, V. P. and V. I. Marchenko, "Effectiveness of Ultrasonic Vibrations Applied During the Hot Pressing of Iron Powder." Soviet Powder Metallurgy and Metal Ceramics, 1971, No. 12, p. 967-969.

The effectiveness of ultrasonics applied during hot pressing of iron powder, in terms of powder shrinkage, was shown theoretically to depend on specimen height, particle size, die wall pressure, apparent density, and interparticle friction (which decreases with increasing temperature). Experimental data, in close agreement with theoretical predictions, showed reduced ultrasonic effect with increased temperature.

Powder Metallurgy

130. Thomas, J. G. and N. Maropis, "Fabrication of Heat Exchanger Tubing of Powdered Metals." Research Report 72-6, Aeroprojects Inc., OSW Contract 14-30-2567, March 1972.

High-strength, high-density cupro-nickel (88.5 Cu, 10 Ni, 1.5 Fe) tubing was fabricated from elemental powders which were mixed, blended with gel-type binder and water, and extruded at a ratio of 15:1 and extrusion rate of 20-25 ft/min, with 15-kHz ultrasonic activation of the die at about 1500 acoustical watts and simultaneous 20-kHz activation of the mandrel at about 200 acoustical watts. After sintering, the tubes showed densities of 85-90% of theoretical. Final sizing to 0.75 in. OD by 0.035-in. wall thickness by ultrasonic tube drawing produced tubing with 98-99% of theoretical density and strengths equivalent to those of wrought tubing. Avenues for further processing development were delineated.

B. METAL REMOVAL

General

131. Zakharov, V. I., V. Ya. Matveev, E. N. Zhustarev, and M. Ya. Friedkin, "Metal Cutting with the Additional Application of Ultrasonic Oscillations." Vestnik Mashinostroeniya, Vol. 41, July 1961, p. 62-65. (In Russian)

Ultrasonic application during milling and thread cutting, particularly of difficult-to-work materials, was found to significantly reduce cutting forces, increase machine tool stability, and permit closer tolerances. During thread cutting, it minimized possible blocking of the tool during back motion. Best results were obtained with the vibration transmitted longitudinally to the cutting tool. The cutting tool design should be modified for ultrasonic excitation.

132. Brown, G. C., "Ultrasonics for Machining." 1962 IRE International Convention Record, New York, March 26-29, 1962, p. 13-23.

In addition to discussion of ultrasonic slurry machining, brief review is given of ultrasonically assisted cutting tools, said to be in the research stage and 2-3 years from industrial utility. Ultrasonic application to rotating, multiple-edge cutting and to single-point cutting was said to reduce friction between tool and workpiece, thus reducing heat concentration, and also to alter the stress pattern at the tool edge. Ultrasonic grinding relieved wheel loading and high localized surface temperatures. Ultrasonic deburring was effective for removing minute burrs. Such techniques offered new approaches to solving industrial problems.

133. Rozenberg, L. D., V. F. Kazantsev, L. O. Makarov, and D. F. Yakhimovich, Ultrasonic Cutting. Akademii Nauk, Moscow, 1962. (Translation by J. E. S. Bradley, Consultants Bureau, New York, 1964)

This book is devoted primarily to ultrasonic slurry machining and its applications in cutting ceramics, cermets, glass, quartz, jewels, and the like, and to a minor extent in the cutting of hard metal alloys. Brief mention is made of ultrasonic application to electrical and electrochemical machining techniques. The detailed discussions of the theory and design of ultrasonic machine tools are of universal interest in ultrasonic equipment design for a variety of metal removal operations.

Metal Removal - General

134. Markov, A. I., Ultrasonic Machining of Intractable Materials. Mashgiz, Moscow, 1962. (Translation by Scripta Technica Ltd., Iliffe Books Ltd., London, 1966)

The major part of the book is a comprehensive presentation on ultrasonic slurry machining. A brief Part II covers the use of sonic and ultrasonic vibrations as an aid to conventional metalworking, including grinding, turning, thread cutting, milling, and drilling. Much of the material deals with prior published literature; new information is reviewed below under appropriate headings.

135. Opitz, H., "Machining Research as a Contribution to Economical Manufacturing." C.I.R.P.-Annalen, Vol. 12, Jan. 1963, p. 4-24.

In experiments using a 20-kHz magnetostrictive transducer to activate a cutting tool, ultrasonic application in the direction of the cutting velocity produced a smoother cut surface and smoother continuous chips and resulted in less tool edge buildup. The effect decreased with increasing cutting speeds, and at 200 m/min no difference in ultrasonic and non-ultrasonic cutting was detectable. Practical application to large workpieces was indicated to be limited by high apparatus costs and by available transducer power. The process appeared to be particularly applicable to machining involving small chip cross sections and low cutting speeds, as in grinding and thread cutting.

136. Devine, J. and W. B. Tarpley, "Ultrasonic Metal Removal." 83rd Meeting, Acoustical Society of America, Buffalo, N. Y., April 18-21, 1972.

Ultrasonic application to metal removal processes including lathe turning, boring, thread cutting, and twist drilling was discussed in terms of equipment development and results achieved. With single-point cutting, stated advantages were increased metal removal rates, reduced tool forces, elimination of chatter, improved surface finish, and improved machinability of difficult-to-cut alloys. Ultrasonic activation of a fluted twist drill provided significant reduction in torque and thrust, thus minimizing tool breakage, increased metal removal rates, facilitation of chip expulsion, cleaner hole break-out, and drilling of greater hole depths without tool withdrawal.

Turning

137. Voronin, A. A. and A. I. Markov, "Effect of Ultrasonic Vibrations on Machining of Heat-Resistant Alloys." Stanki i Instrument, 1960, No. 11, p. 15-17. (In Russian)

Ultrasonic radial activation of the cutting tool at 22 kHz during turning of heat-resistant steel alloys had variable effects, depending on the vibratory intensity. At high power levels (2-3.5 kw), tool life decreased, apparently because of significant increase in cutting temperature. At lower power (1 kw), tool life increased fourfold. The coefficient of chip contraction was also reduced, indicating reduced rate of plastic deformation in the shear layer. The ultrasonically cut surface had a mat finish, while that non-ultrasonically cut was bright and glossy.

138. Isaev, A. I. and V. S. Anokhin, "Ultrasonic Vibration of a Metal Cutting Tool." Stanki i Instrument, 1961, No. 5, p. 48-53. (In Russian; cited in Ref. 134)

An 8-kw, 18-kHz magnetostrictive transducer was used to vibrate a lathe tool in several directions, all in a plane normal to the lathe axis. Mild steel and nickel-chrome steel were turned at speeds up to 70 m/min, feeds up to 0.13 mm, and depths of cut up to 2 mm. With tangential vibration, surface finish was reduced from 49-65μ to 1-2μ, edge build-up on the tool was eliminated, and workhardening of the material was reduced. All three components of cutting force were reduced, the effect becoming less pronounced as cutting speed was increased. Cutting temperature was higher with ultrasonic activation.

139. Kumabe, J., "Study on Ultrasonic Internal Grinding by Using the Longitudinally Vibrated Grinding Wheel, I." Japanese Society of Mechanical Engineers, Trans., Vol. 27, Sept. 1961, p. 1404-1411. (In Japanese)

The mechanism of ultrasonic cutting with a single-point cutting tool vibrating in the transverse direction was analyzed theoretically and experimentally. Cutting was carried out at a frequency of 20.3 kHz, vibratory amplitudes from 7 to 16.5 μ, depths of cut of 0.02 to 0.125 mm, and speeds up to 100 m/min. Ultrasonic application significantly decreased required cutting forces, particularly at the lower speeds, and increased the cutting ratios. However, ultrasonic friction between tool and workpiece induced high temperatures at the tool edge and accelerated tool wear. It was suggested that a grinding wheel would perform more smoothly than a single-point cutting tool under ultrasonic influence.

Turning

140. Kumabe, J., "Study on Ultrasonic Cutting." Japanese Society of Mechanical Engineers, Trans., Vol. 27, Sept. 1961, p. 1389-1404. (In Japanese)

It was established that in ultrasonic metal cutting the direction of vibration should generally be in the direction of the cut. Principles and equations were developed for designing ultrasonic systems operating in the longitudinal and torsional modes, with both exponential and conical horns. The systems could be fixed statically or rotated. Lathe attachments were designed for operation at frequencies in the range of 10-40 kHz. A critical cutting speed, beyond which no further improvement with ultrasonic cutting was achieved, was found to be a function of frequency and amplitude.

141. Danielyan, A. M. and Yu. A. Gritsaenko, "Vibratory Cutting." Machines and Tooling (USSR), Vol. 33, June 1962, p. 51-52.

The status of ultrasonic machining of heat-resistant alloys was reviewed, and conflicting data were noted, indicative of a process in its first development stage. Further research was indicated to establish optimum frequency, power, vibratory direction, as well as ultrasonic effects on plastic deformation, tool wear, forces and temperatures, work-hardening, and surface finish.

142. Markov, A. I., Ultrasonic Machining of Intractable Materials. Mashgiz, Moscow, 1962. (Translation by Scripta Technica Ltd., Iliffe Books Ltd., London, 1966)

On the basis of available information on ultrasonics applied during turning of heat-resistant alloys, the author concluded that practical application of the process was held back by the complexity, inadequate strength, and high cost of existing ultrasonic equipment. The necessity for providing a rigid system in order to obtain maximum results was emphasized.

143. McKaig, H. L., "Applications of Ultrasonics to Metal Forming and Rolling." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 33-36.

Ultrasonic activation of a lathe tool during turning of 2024 aluminum alloy, 4340 steel, and unalloyed titanium resulted in up to 30% reduction in cutting force, elimination of tool chatter, and altered surface finish. It was suggested that fatigue strength may be improved by ultrasonic turning.

144. Skelton, R. C. and S. A. Tobias, "A Survey of Research on Cutting with Oscillating Tools." Advances in Machine Tool Design and Research, Tobias and K. K. Koeninsberger, Eds., Macmillan Co., New York, 1963, p. 5-16. Also "Putting Vibrations to Work." Metalworking Production, Vol. 106, Oct. 24, 1962, p. 65-68.

Turning

Review of available literature (primarily Russian) on controlled vibration of a lathe tool indicated effects such as improved chip breaking, reduction in cutting forces, increase in tool life, decrease in cutting temperature, elimination of edge buildup on tool, reduction in workhardening, and increase in cutting fluid effectiveness. The magnitude of the effects was reported to depend upon the vibratory amplitude, frequency, and direction, its phase relation to the previous cut, and the normal cutting parameters of feed, speed, depth of cut, etc. Vibration was usually in the direction of feed, since surface finish was otherwise adversely affected. Frequencies ranged from a few hertz to over 20 kHz.

145. Nerubay, M. S., "Investigation of the Effectiveness of Ultrasonic Vibration of the Tool When Machining Heat-Resistant and Titanium Alloys." Kuybyshev Aviatsionnye Institut, Trudy, 1963, No. 18, p. 15-27. (Air Force Translation FTD-MT-24-162-70)

Several difficult-to-machine alloys were turned on a lathe under the influence of vibration at 18-25 kHz in a radial mode. The chips showed reduced longitudinal shrinkage, edge buildup on the tool was minimized, and quality of the cut surface was improved. At low amplitudes, temperature in the cutting zone decreased, and cutting force decreased. At high amplitudes, temperatures and forces increased, and there was greater workhardening in the cut layer.

146. Balamuth, L., "Recent Developments in Ultrasonic Metalworking Processes." SAE Paper 849G, Air Transport and Space Meeting, New York, April 27-30, 1964. Also Balamuth, "Ultrasonic Metalworking." American Machinist, Vol. 108, April 13, 1964, p. 136-138.

Preliminary experiments in single-point cutting on an aluminum block with a lathe tool mounted on a surface grinder resulted in considerable chatter in making a 0.060-in.-deep cut. With 20-kHz vibration of the tool, tool forces were reduced, chatter marks completely disappeared, and the cut was smooth.

147. Aeroprojects Inc., "Investigation of Vibratory Excitation of Cutting Tool During Lathe Turning." Research Report 64-76, Sept. 1964.

Experiments were carried out in turning several steel alloys, including 4340 and Vasco-Jet 1000, with 20-kHz ultrasonic excitation of the cutting tool in a direction tangential to the surface being cut. Tool force reductions ranged up to 60%; the effect decreased with increasing cutting speed, feed, and depth of cut, suggesting that higher power should be used at the greater metal removal rates. At the higher cutting speeds, tool life was increased. The work established the practicability of installing an ultrasonic system on a standard lathe with minimum modification.

Turning

148. Kristoffy, I. I., R. L. Kegg, and R. R. Weber, "Influence of Vibrational Energy on Metalworking Processes." Report AFML-TR-65-211, Cincinnati Milling and Grinding Machines, Inc., Cincinnati, Ohio, Air Force Contract AF 33(657)-10821, July 1965.

Ultrasonic vibration of the cutting tool at 24 kHz in the tangential direction effected force reductions up to 90% in turning (end facing) of aluminum alloy, copper, steel, and brass. The effect was reduced at increased feeds and cutting speeds but was increased with increasing vibratory amplitude. In addition, chatter was inhibited, and surface finish and chip formation were improved.

149. "Ultrasonic Energy Aids Turning, Grinding, Machining." Steel, Vol. 157, July 12, 1965, p. 58-60.

Ultrasonic application to lathe turning was said to be technically feasible because of such demonstrated benefits as 10-50% tool force reduction (depending on power input), improved surface finish, especially with aluminum and titanium alloys, and elimination of tool chatter. Recent developments in ultrasonic equipment design appeared to offer sufficient refinements for field evaluation of the process by industry.

150. Dohmen, H. G., "Machining Research with Ultrasonically Excited Turning Tools." Industrie-Anzeiger, Vol. 88, Jan. 26, 1966, p. 115-122. (In German)

In turning aluminum and steel cylinders with 20-kHz ultrasonically activated tools, surface finish was significantly improved at the lower cutting speeds, smoother, more continuous chips were obtained, and edge buildup was completely eliminated. Surface finish was improved only when the direction coincided with the direction of the principal cutting force, not in the transverse direction. Several hypotheses for explanation of the effects were presented. Successful ultrasonic application to other chip-making processes, such as broaching and reaming, was postulated.

151. Bayles, W. H., "Ultrasonic Machining of Hard Ceramics: An Engineering Evaluation." Research Report 68-63, Aeroprojects Inc., Oct. 1968.

Ultrasonic single-point machining of hard ceramics was demonstrated by means of linear unidirectional cuts with a diamond tool on an alumina composition. Ultrasonic tool activation in a direction longitudinal, vertical, or transverse to the direction of cut reduced tool forces by as much as 80% and produced wider and deeper cuts, indicating increased rate of material removal. Tool chatter was effectively eliminated. Ultrasonic power requirements were low, approximately 25 electrical watts input to a magnetostrictive transducer. Requirements for an ultrasonic machining array for installation on a standard metalworking lathe were evolved.

Turning

152. Maropis, N. and J. Devine, "Development and Evaluation of Ultrasonic I.D. (Boring) Single-Point Machining System." Research Report 72-7, Aeroprojects Inc., Feb. 1972.

An experimental ultrasonic boring system was developed utilizing a 28-kHz axial-torsional mode-conversion transducer-coupling array delivering up to 450 acoustical watts power to interchangeable cutting tools. Evaluation in machining 2024-T6 aluminum alloy and 1018 HR steel showed substantial tool force reduction (21-71% depending on material, machining rate, and tool type). Machined surfaces were smoother than with non-ultrasonic cuts, subsurface material disturbance was markedly reduced, and chips had smoother edges and greater curl radius. The equipment was installed on a lathe in an AEC plant for further evaluation.

Drilling

153. Marshall, N. K., "An Ultrasonic Drill for Boring Small Holes in Hard Materials." Industrial Diamond Review, Vol. 18, Jan. 1958, p. 17-19. Also Marshall, "Waveform Rotates Ultrasonic Jack Hammer Drill." Electronics, Eng. Ed., Vol. 31, Jan. 17, 1958, p. 116-117. Also Marshall, "Drilling Small Holes by the Ultrasonic Method." Machinery, Vol. 92, Feb. 14, 1958, p. 379-380.

A new technique for drilling small-diameter precison holes in hard materials involved the use of a 28-kHz magnetostrictive transducer and brass exponential horn driving a diamond-paste-loaded brass drill in a rotary "jack-hammer" action. The assembly was suspended from an adjustable bracket by a resilient support. The hole was started dry, then diamond paste was added to the drill and was renewed about every 4 min. The drill substantially speeded up the drilling process and increased the accuracy of the finished hole.

154. Zhustarev, E. N., V. I. Zakharov, V. Ya. Matveev, and M. Ya. Freidkin, "The Cutting of Metals with the Application of Ultrasonics." The Application of Ultrasonics in Engineering Technology, TsINTI, Moscow, 1960, p. 235-243. (In Russian; cited in Ref. 134)

Ultrasonic application to twist drills of normal geometry was obseerved to provide no beneficial effect, and it appeared advantageous to use drills with greater core diameter in order to withstand the static and dynamic loads. With ultrasonic activation of flat drills of high-speed steel, the cutting speed increased considerably without increase in axial force. The chip was more easily broken up and did not adhere to the drill.

Drilling

155. Danielyan, A. M. and Y. A. Gritsaenko, "Vibratory Cutting." Machines and Tooling (USSR), Vol. 33, June 1962, p. 51-52.

Several ultrasonic drilling investigations were reviewed. Drilling of small and medium holes with ultrasonic vibrations increased the drill life 2 to 4 times, one investigation showed. Another stated that drilling of similar holes in stainless steel nuts with ultrasonics trebled the drill life. Even longer life was attained in machining creep-resistant alloys when the vibrations were at right angles to the machine surface and had small peak-to-peak amplitudes. In deep-drilling with a carbide-tipped drill, it was possible to increase drill feed rate 30% with the same drill life.

156. Peacock, J., A. Kuris, and L. Balamuth, "Ultrasonics and Metal Removal." American Machinist, Vol. 106, Aug. 20, 1962, p. 85-88. Also Balamuth, "Ultrasonic Vibrations Shape Metals." SAE Journal, Vol. 71, July 1963, p. 36-41.

A drilling experiment was carried out with a longitudinally vibrating transducer mounted on a drill press and, using a carbide drill, attempting to bore a hole in an aluminum oxide grinding wheel. The carbide drill itself penetrated about 1/4 of the depth of the wheel before beginning to be ground itself. Then ultrasonic vibrations were applied, and a clean hole was produced in 10 seconds, using the dulled drill. Cooling water spray was applied, and particles from the wheel may have acted as an abrasive slurry, aiding the process.

157. Legge, P., "Ultrasonic Drilling of Ceramics with Diamond Impregnated Probes." Report AERE-M 1150, Atomic Energy Research Establishment, Harwell, Berkshire, England, Feb. 1963.

A standard ultrasonic drill (as used with slurry machining) was modified to incorporate a rotary chuck mounted on the drill bed so that the workpiece could be rotated beneath the vibrating probe. This was used with both solid and hollow probes which were diamond-impregnated along their cutting surfaces for drilling holes or for trepanning. Annular grooving and thread cutting was also said to be feasible with this equipment. The device was effective in drilling precise holes in hard materials, such as uranium oxide and carbide, without chipping or cracking and with greater accuracy than could be achieved with the slurry technique. For deep drilling, a kerosene coolant was used to flush out the grindings.

158. "Ultrasonic Drilling with a Diamond Impregnated Probe." Ultrasonics, Vol. 2, Jan. 1964, p. 1-4.

In further developments of ultrasonic drilling without abrasive slurry, the ultrasonic unit was built into a standard milling machine. It was observed

that too much static pressure on the drill damped out drill motion completely and cutting stopped. Holes up to 1/2-in. diameter were drilled with a solid drill; larger holes could be made with a trepanning action. Cutting accuracy was usually within 0.001 in. A slotting attachment was also developed and effectively used.

159. Legge, P., "A Universal Ultrasonic Machine Tool for Glass and Ceramics." Report AERE-M-1720, Atomic Energy Research Establishment, Harwell, Berkshire, England, Feb. 1966. Also Legge, "Machining Without Abrasive Slurry." Ultrasonics, Vol. 4, July 1966, p. 157-162.

The 20-kHz ultrasonic tool developed for use with diamond impregnated probes was redesigned to provide rotation of the transducer-coupling system through a slip ring and brush assembly. Special tools were fabricated and effectively used for drilling, end milling, slotting, trepanning, internal and external grinding, and internal and external thread cutting of hard ceramics and glass. Substantially improved accuracy was obtained at rates comparable to those achieved with other techniques. Rotational rates significantly higher or lower than 1000 rpm retarded the rate of penetration, apparently because of damping of the vibration.

160. Pruder, G. D. and H. D. Edelson, "Ultrasonic Application to Drilling of High-Strength Metal Alloys." Research Report 68-26, Aeroprojects Inc., April 1968.

A 20-kHz ultrasonic system exciting a fluted twist drill in the axial mode was installed on a standard drill press frame and used in drilling 1/2-in. holes in 2-in.-long rods of 6Al-4V titanium alloy. Extensive data obtained established: metal removal rates increased at least fourfold, reduced thrust and torque loads, essential elimination of chatter, alleviation of chip packing, no difficulty in drilling through depths of four diameters, improved hole accuracy, and possibly extended drill life. In view of relatively low power requirements, it appeared practical to incorporate ultrasonic systems into conventional drilling machinery.

161. Aeroprojects Inc., "Ultrasonic Riveting and Ultrasonic Drilling and Countersinking." Research Report 69-15, April 1969.

An ultrasonically activated twist drill was used to drill and countersink 1/8-in. and 1/4-in. holes in 6Al-4V titanium alloy sheet material. Without lubricant, the drilling rate was increased four- to five-fold; with lubricant, there was about a sixfold increase. Torque and thrust were significantly reduced, especially at the lower power levels. Extrapolation of the data indicated that 200 electrical watts input to a ceramic transducer would provide adequate power for hole sizes up to 1/2 in. No significant effect was noted on drill life, hole accuracy, or hardness of the sheet adjacent to the hole.

Drilling

162. "'Woodpeckering' With Gundrills." American Machinist, Vol. 113, July 28, 1969, p. 31.

Using axial vibration of the tool at 7-8 kHz, gun drilling in high-strength steel was accomplished at twice the feed rates normally achieved. The drills were about 1/4-in. diameter and larger and of conventional gun-drill point geometry. Subsequently ultrasonic systems were developed for use on the slide of a six-spindle automatic lathe. The process was introduced into fuel-equipment factories in Russia. Reported accuracies were about 0.002 in. diametral variation, hole straightness to 0.00008 in., roundness to 0.00012 in., taper to 0.0006 in., and not more than 0.002 in. deviation in concentricity.

163. Tyrrell, W. R., "Rotary Ultrasonic Machining with Diamond Tools." Proc. International Industrial Diamond Conf., Chicago, Oct. 20-22, 1969, p. 275-280.

Rotary ultrasonic machines utilizing diamond tools were extensively developed in the U.S.A. The components consist of a power supply, rotary ultrasonic head assembly, and diamond tools, which can be used in a conventional milling machine or drill press. Use of such tools in drilling, milling, and threading was described. The equipment was being successfully used to drill glass, hard ceramics, and boron-epoxy composites. Advantages were said to include faster material removal, less breakage, less tool wear, elimination of frequent back-off of the tool, and negligible loading of the diamonds. Typical applications were discussed.

164. Tyrrell, W. R., "A New Method for Machining Hard and Brittle Materials." SAMPE Quarterly, Vol. 1, Jan. 1970, p. 55-59.

A rotary ultrasonic machine tool was described consisting of a power supply, a rotary head assembly, and diamond tools that could be securely attached to the head. The device was used for drilling difficult-to-machine materials. This device substantially increased drilling rates, increased drilling accuracy, and permitted longer tool life. Examples cited included drilling of alumina, beryllia, glass, ferrite, and quartz.

165. Shoh, A., "A New Look at Ultrasonic Metal Drilling." SAMPE Quarterly, Vol. 1, July 1970, p. 11-16.

The rotary ultrasonic drill with diamond tools was effectively applied to the drilling of titanium, with 50-100% improvement in material removal rate and in some cases a threefold increase in tool life. Equipment was developed for adapting conventional machines to the ultrasonically assisted operation. The process was said to be effectively used in production with substantial time and cost savings. Application to other materials, to holes larger than the present 1/4-in. limitation, and to other types of cutting appeared feasible. Tool material and geometry should be investigated.

Drilling

166. Doran, J. H., F. Hanley, and M. S. Howeth, "Manufacturing Methods for Machining Processes for High Modulus Composite Materials." First Quarter Report, General Dynamics, Convair Aerospace Div., Fort Worth, Texas, Air Force Contract E33615-70-C-1427, Aug. 1, 1970; Second Quarter Report, Nov. 1, 1970.

During investigation of machining methods for boron-epoxy and boron-epoxy/titanium laminates for flight vehicle structure, the rotary ultrasonic drill with diamond tools was examined. By this means, up to threefold increases in cutting rates were obtained and, when used with a coolant, tool wear was reduced. The process was proposed for drilling, reaming, countersinking, and milling of boron-epoxy. It was not effective in cutting through the titanium laminate due to the presence of the non-cutting dead center of the drill.

167. Aeroprojects Inc., "Ultrasonic Twist Drilling: Background and Potential." Jan. 1971. Also "Ultrasonic Twist Drilling." NAVMIRO Manufacturing Technology Bulletin No. 20, Naval Material Industrial Resources Office, Philadelphia, July 1971.

Ultrasonic twist drilling was said to constitute a major breakthrough in drilling technology. Data provided on ultrasonic drilling of aluminum alloys, copper, steel, cast iron, and titanium alloys indicated decreased torque and thrust loads, substantially increased metal removal rates, facilitated chip removal so that deeper holes could be drilled without tool withdrawal, extended drill life, virtual elimination of tool chatter, and alleviation of lubrication problems. The process was noted to have potential not only to solve recalcitrant metal penetration problems, but also to increase productivity in ordinary drilling.

168. Cusumano, J., "Ultrasonic Machining." Interim Reports IR-703-1 (I, II, III, V), Grumman Aerospace Corp., Bethpage, N. Y., Air Force Contract F33615-71-C-1706, Sept. 30 and Dec. 31, 1971; March 31 and Sept. 30, 1972.

Comprehensive evaluation of ultrasonic machining (drilling, countersinking, and reaming) of holes up to 3/8-in. diameter in boron-reinforced composites and laminates of titanium with such composites was undertaken, using rotary ultrasonic machine tools (stationary and portable) with diamond core drills. Effort was expended in optimizing drilling parameters, ultrasonic power requirements, type of coolant, and process variables in terms of tool life, tolerance control, surface integrity, and economical production. Ultrasonic activation significantly reduced drilling time, torque and thrust loads, and tool wear, improved surface finish, minimized drill retraction for dislodging the core, and minimized clogging of the drill surface. Step drilling was required to drill through titanium greater than 1/8 in. thick. Ultrasonic drilling had no significant effect on material properties. Based on tool cost, tool life, and drill time, ultrasonics effected substantial savings in cost per hole.

Milling

169. Zhustarev, E. N., V. I. Zakharov, V. Ya. Matveev, and M. Ya. Freidkin, "The Cutting of Metals with the Application of Ultrasonics." The Application of Ultrasonics in Engineering Technology, TsINTO, Moscow, 1960, p. 235-243. Also "Metal Cutting with the Additional Application of Ultrasonic Oscillations." Vestnik Machinostroeniya, Vol. 41, July 1961, p. 62-65. (In Russian)

Ultrasonic application during milling of copper and stainless steel significantly facilitated cutting, particularly when the vibration was transmitted longitudinal to the principal cutting blade. Cutting force was substantially reduced, the depth of cut was approximately doubled, and tool stability was increased to permit closer tolerances in cutting hard materials. The optimum geometry of the cutting tool was said to change with ultrasonic application.

170. Vaughn, R. L., L. J. Quackenbush, and L. V. Colwell, "Shock Waves and Vibration in High-Speed Milling." Paper 62-WA-282, ASME Winter Annual Meeting, New York, Nov. 25-30, 1962.

Study was made of self-excited high-frequency vibrations induced in cylindrical rods of brass, steel, aluminum, and titanium during high-speed milling. An apparent correlation between frequency and chip fragmentation was noted. The frequency increased with increasing speed and/or thickness of cut, and could be predicted by shear-wave theory. On the basis of this study, it appeared feasible to superimpose high-frequency vibrations during cutting to inhibit chatter and to reduce power requirements.

171. Balamuth, L., "Recent Developments in Ultrasonic Metalworking Processes." SAE Paper 849G, Air Transport and Space Meeting, New York, April 27-30, 1964. Also Balamuth, "Ultrasonic Metalworking." American Machinist, Vol. 108, April 13, 1964, p. 136-138.

Ultrasonic milling with both steel and carbide end mills, in taking a cut 1/4 in. deep in 4340 steel, produced significantly improved surface finish and reduced cutting forces. Cessation of vibration during a pass resulted in immediate fracture of the cutter. The process offered promise of improved production rates and improved machining of hard-to-work materials.

172. Tyrrell, W. R., "A New Method for Machining Hard and Brittle Materials." SAMPE Quarterly, Vol. 1, Jan. 1970, p. 55-59.

Ultrasonic milling, surface grinding, and slotting were accomplished with ultrasonic activation of a diamond impregnated tool. Required pressure was reduced, cutting rates were increased, and the operation was smoother.

Broaching

173. Balamuth, L., "Recent Developments in Ultrasonic Metalworking Processes." SAE Paper 849G, Air Transport and Space Meeting, New York, April 27-30, 1964. Also Balamuth, "Ultrasonic Metalworking." American Machinist, Vol. 108, April 13, 1964, p. 136-138.

Broaching of a square hole in 0.050-in.-thick brass was accomplished using a hollow broach with the workpiece vibrated at 20 kHz with an amplitude of 0.002 in. Traverse time was decreased from 5 to 3 sec, air pressure (for force application) decreased from 35 to 15 psi, and surface finish improved from 40 to 20 μin.

Thread Cutting

174. Zhustarev, E. N., V. I. Zakharov, V. Ya. Matveev, and M. Ya. Freidkin, "The Cutting of Metals with the Application of Ultrasonics." The Application of Ultrasonics in Engineering Technology, TsINTI, Moscow, 1960, p. 235-243. (In Russian)

Ultrasonic thread cutting of copper, stainless steel, and heat-resistant alloy was accomplished with a 23-kHz transducer-coupling system mounted on a lathe. Good-quality threads were obtained even in a difficult material such as copper. Torque was reduced to approximately half its non-ultrasonic value. The vibration prevented jamming and breaking of the taps during withdrawal.

175. Zakharov, V. I., V. Ya. Matveev, E. N. Zhustarev, and M. Ya. Freidkin, "Metal Cutting with the Additional Application of Ultrasonic Oscillations." Vestnik Machinostroeniya, Vol. 41, July 1961, p. 62-65. (In Russian)

In cutting threads under ultrasonic influence, the maximum torque on the tool was reduced by as much as 40% over conventional cutting, and surface finish was improved. In addition, binding of the tool during back motion was alleviated.

176. Colwell, L. V., "Application of Ultrasonics to Metal Cutting." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 7-10.

Ultrasonic activation of a 1/4-20 tap during tapping of aluminum, brass, copper, magnesium, and low-carbon steel reduced the required torque within the range of 73-93%. Little improvement was obtained with René 41.

Thread Cutting

177. McKaig, H. L., "Applications of Ultrasonics to Metal Forming and Rolling." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 33-36.

In tapping experiments, 500-watt ultrasonic activation of a 1/2-in. tap resulted in 30% reduction in required torque for Monel, more than 20% reduction for copper, and 12% for steel. In addition, tearing of the workpiece was alleviated with ultrasonics.

178. Poduraev, V. N. and A. A. Suvorov, "Tapping Heat-Resisting Steels With Superimposed Ultrasonic Vibrations." Machines and Tooling (USSR), Vol. 36, Feb. 1965, p. 27-29.

Investigations were carried out in ultrasonic tapping of blind holes in stainless steel nuts at a frequency of 20 kHz and amplitude of 20 μm. Friction and torque were substantially reduced, chip formation was simplified and chip expulsion facilitated, flow of coolant to the cutting zone was improved, surface finish was improved, and output was increased 1.5 to 2.0 times.

179. Mikhailiuk, E. A., "Thread Cutting by Taps in Titanium Alloys with Application of Ultrasonic Vibrations." Problems in the Technology of Aircraft Production, Kuybyshev Aviatsionnye Institut, Trudy, 1965, p. 227-233. (In Russian)

Experiments were carried out using ultrasonic vibration of the screw tap when cutting threads in a titanium alloy. Operation of the device was described in detail and test results were analyzed. During vibration of the tap, the overall torque decreased significantly, particularly under longitudinal vibrations. The vibratory energy prevented welding and sealing of the thread recess and prevented the cut metal from adhering to the rear surface of the cutting teeth.

180. Tyrrell, W. R., "A New Method for Machining Hard and Brittle Materials." SAMPE Quarterly, Vol. 1, Jan. 1970, p. 55-59.

Using an ultrasonic rotary tool, internal and external threads were cut in various ceramics such as alumina. The workpiece was held in a rotary chuck which was motor-driven and incorporated a lead screw for raising or lowering the chuck one thread pitch per revolution. A full depth of thread was cut in one pass, and cutting rates up to four threads per minute were achieved.

Grinding

181. Colwell, L. V., "The Effects of High Frequency Vibrations in Grinding." ASME Transactions, Vol. 78, May 1965, p. 837-846.

Investigations in vibratory grinding of steel and titanium alloy were carried out using a 10-18 kHz transducer mounted on a reciprocating-table surface grinder so that the specimen vibrated radially with respect to the wheel. The ultrasonically ground specimens showed substantially improved surface finish (from 40 to 16 μin.); grinding temperatures were markedly reduced (from 475° to 255°F), and indications of excessive heat were essentially absent. Residual stresses appeared to be substantially less, and the incidence of stress cracking was markedly reduced. On the negative side, the grinding wheel broke down more rapidly with applied vibration.

182. Chernousenko, A. P., "Vibration Grinding of Hard Alloy." No. M-57-35/16, VINITI, Moscow, 1957. (In Russian; cited in Ref. 134)

Vibration at 18 kHz and 0.05-mm amplitude was applied parallel or perpendicular to the centerline of the grinding wheel during grinding of hard steel. Surface finish was improved and cracks in the workpiece were eliminated, but productivity decreased by 40%. No effect on wheel wear was detectable.

183. Voronin, A. A. and A. I. Markov, "Effect of Ultrasonic Vibrations on Machining of Heat-Resistant Alloys." Stanki i Instrument, 1960, No. 11, p. 15-17. (In Russian; cited in Ref. 134)

Ultrasonic activation at 21 kHz of the grinding wheel during grinding of steel alloys had a favorable effect on surface finish, the smoothness being increased by 1.5 classes. Grinding wheel wear was substantially increased under ultrasonic influence.

184. Voronin, A. A., A. I. Markov, and M. A. Shcherbak, "The Effect on Cutting of Ultrasonic Vibration in Sharpening of Tools." Machines and Tooling (USSR), Vol. 32, Feb. 1961, p. 15-17.

High-speed steel and carbide cutting tools sharpened under ultrasonic influence were subsequently used to cut heat-resistant alloys. A 22-kHz nickel-stack transducer contacted the wheel of a surface grinder, and the tips were ground along the rake face and clearance edges without cooling. Profilographs of the surfaces after grinding showed that the microroughness was almost halved by ultrasonic grinding. In continuous longitudinal turning (without vibration) of heat-resistant alloys, the ultrasonically ground tools exhibited substantial increase in life and permitted increased cutting speeds. The greatest effect was in the area of highest cutting speed; at 25 m/min, tool life was extended more than 100%.

Grinding

185. Bredin, H. W., "Ultrasonics Creates Major Innovation in Surface Grinding." Machinery, Vol. 67, April 1961, p. 150-152. Also Peacock, J., "Ultrasonics Ups Grinding Efficiency." American Machinist, Vol. 105, March 20, 1961, p. 124-125.

Ultrasonic vibration at 20 kHz, applied close to the cutting surface of a grinding wheel and acting through a water-base coolant, was used to prevent metal particle loading of the wheel. The abrasive grains thus remained free-cutting for longer times, wheel wear was reduced and wheel life extended. With a forged steel part, grinding time was reduced from 30 to 17 min, and wheel redressing, formerly necessary after every 3 parts, was not required after a run of 11 parts. The ultrasonic technique also minimized chatter and markedly improved accuracy and surface finish. With 303 stainless steel, a 35 μin. surface was reduced to 8 μin., and grinding wheel wear was reduced to one-sixth of the conventional wear.

186. Kumabe, J., "Ultrasonic Internal Grinding Using a Longitudinally Vibrating Grinding Wheel, II." Japanese Society of Mechanical Engineers, Trans., Vol. 27, Sept. 1961, p. 1412-1418. (In Japanese)

Specimens of aluminum, copper, brass, and high-speed steel were ultrasonically ground using a longitudinally vibrating grinding wheel at a frequency of 20 kHz and amplitudes up to 22 μ. The investigation covered surface speeds up to 120 m/min. The rate of material removal was markedly accelerated by ultrasonic application, an effect which increased with increasing amplitude and decreased with increased cutting speed. Powdery chips were scattered during grinding, and wheel loading was minimized.

187. Brown, G. C., "Ultrasonics for Machining." IRE International Convention Record, Vol. 10, Pt. 6, 1962, p. 13-23.

Experiments in ultrasonically assisted grinding indicated alleviation of such problems as high wheel loading and high localized workpiece temperatures that result in warping and distortion. Most effective results were obtained with the transducer coupled to the grinding wheel of a surface grinder. Although still in the development stage, the process appeared to have good potential.

188. Markov, A. I., Ultrasonic Machining of Intractable Materials. Mashgiz, Moscow, 1962. (Translation by Scripta Technica Ltd., Iliffe Books Ltd., London, 1966)

Study of the wear of grinding wheels showed that ultrasonic vibration increased wear by a factor of about 1.5. For example, with one type of wheel, the ratio of workpiece material removed to that of mean wheel wear decreased from 5.2 without vibration to 4.6 with vibration; with another wheel type, the

ratio decreased from 2.6 to 1.3. In further experiments, high-speed cutting tools were sharpened on a grinding wheel with and without ultrasonic vibration and were used in non-ultrasonic cutting of heat-resistant alloys. Life of the ultrasonically sharpened tools was substantially greater, the effect being most pronounced at the lower cutting speeds.

189. Roney, R. N. and D. Giardini, "Final Report on Imposed High Frequency Vibrations and Their Effect on Conventional Grinding of High Thermal Resistant Materials." Report ASD-TDR-63-203, Sheffield Corp., Dayton, Ohio, Air Force Contract AF 33(600)-40122, Jan. 1963.

Various arrangements and conditions for vibratory grinding were investigated. Best results were obtained with 20-kHz vibration of the wheel. Benefits included lower temperatures, lower grinding power, greater grinding ratios, no impairment of surface finish, no cracking, no effect on fatigue or tensile strength. Internal, external, and surface grinders were modified to incorporate an ultrasonic spindle which vibrated a special wheel and hub assembly, and simulated production runs on several alloys showed increased volume removed in the range of twofold to fivefold.

190. Balamuth, L., "Ultrasonic Vibrations Shape Metals." SAE Journal, Vol. 71, July 1963, p. 36-41.

Trueing of a grinding wheel was accomplished by pressing a vibrating tool against the wheel at low pressure in the presence of a cooling liquid; precise tolerances were achieved at relatively low cost. In another process, grinding was accomplished with the aid of a coolant flowed through the center of a vibrating tool, with the coolant cavitating against the wheel. Temperature drops up to 400°F were thus achieved, the wheel was continually cleaned of metal particles, and improved surface finish on the ground workpiece was obtained. Other approaches involved vibration of the grinding wheel itself to produce cooler grinding, improve surface finish, reduce force requirements, and reduce wheel wear.

191. Colwell, L. V., "Application of Ultrasonics to Metal Cutting." DMIC Report 187, Defense Metals Information Center, Columbus, Ohio, Aug. 16, 1963, p. 7-10.

Ultrasonic activation of the workpiece during grinding of materials such as 52100 steel and U500 alloy reduced residual stresses, decreased power requirements, and reduced tool wear. Other materials showed smoother surface finish and absence of oxide spots indicative of high temperatures.

Grinding

192. Kaliszer, H. and M. Limb, "Application of Ultrasonic Techniques in Grinding Processes." International Journal of Machine Tool Design and Research, Vol. 8, Oct. 1968, p. 189-201.

Ultrasonic treatment at 20 kHz operated through the medium of a coolant to rid the pores of a grinding wheel of metal particle agglomerates. Wheels ultrasonically treated showed no change in permeability after 20 min of grinding time, while untreated wheels deteriorated rapidly and, for harder wheels, cutting was interrupted after 75 min from violent chatter due to increase in frictional forces. With intermittent ultrasonic treatment, the amplitude of chatter vibration decreased abruptly when ultrasonics was turned on and rose again as soon as it was turned off. Wheel wear was much more rapid without ultrasonic treatment. Ultrasonically ground materials showed 65% improvement in surface finish.

Finishing

193. Wright, J. P. "Ultrasonic Deburring." American Machinist, Vol. 101, Feb. 11, 1957, p. 129-136.

Details of ultrasonic deburring were not disclosed but it was said to resemble ultrasonic cleaning, except that higher power and denser media were used. Burrs and sharp edges were attacked first, and smooth flat surfaces were not noticeably affected. No special fixturing was required, and average parts could be processed at the rate of 100 per hour. It was demonstrated to be effective for either commercial or precise tolerances and for radiused edges to 0.0001 in.; surface finish was substantially improved and parts delivered laboratory clean, with no change in physical or chemical properties. Several examples were presented; cost savings were said to amount to as much as 85%.

194. "Deburring with Ultrasound." Steel, Vol. 142, April 7, 1958, p. 102-103.

Ultrasonic deburring was accomplished by immersing the parts in a mild etching solution ultrasonically agitated, followed by cold water rinsing and infrared drying. The process was particularly effective when other methods gave poor results, and deburring costs could be reduced by as much as 98%. Despite the intense scrubbing action, critical dimensions remained unchanged, as did physical and mechanical properties. Tolerances of precision instrument parts were not altered by 0.000005 in.

195. Brown, G. C. and J. N. Behm, "Ultrasonics for Metalcutting." Tool and Manufacturing Engineer, Vol. 30, March 15, 1961, p. 57-60.

Ultrasonic deburring was accomplished using a shaped cutting tool with an abrasive slurry to remove fine burrs, primarily those left by grinding or

lapping. Corner radii could be kept small and surface finishes were generally 10 μin. or less. No damage occurred to adjoining finished surfaces. The process was said to be practical only when conventional tumbling and blasting could not be used.

196. Isaev, A. I. and V. S. Anokhin, "Reaming with Ultrasonically Vibrated Reamers." Machines and Tooling (USSR), Vol. 33, June 1962, p. 27-29.

Ultrasonic reaming was carried out using a 21-kHz magnetostrictive transducer attached to a velocity transformer that converted longitudinal into torsional vibration; the assembly was mounted in a lathe. With appropriate cutting conditions, both surface finish and diametral precision were markedly improved, the more so as vibratory amplitude was increased. Acceptable surface finish was produced at several times conventional cutting feeds and speeds, and reaming time could be reduced by as much as fourfold.

197. Danielyan, A. M. and Y. A. Gritsaenko, "Vibratory Cutting." Machines and Tooling (USSR), Vol. 33, June 1962, p. 51-52.

Russian investigators found that ultrasonic vibrations improved abrasive machining. In lapping metals with abrasive pastes, vibrations increased metal removal rates, improved surface finish, allowed easier access of cutting fluid, and improved abrasive action.

198. Peacock, J., A. Kuris, and L. Balamuth, "Ultrasonics and Metal Removal." American Machinist, Vol. 106, Aug. 20, 1962, p. 85-88.

Ultrasonic honing, utilizing a combination of radial and rotary or rotary and longitudinal motion, demonstrated benefits. The vibratory force made it possible to hone with a minimum of pressure, giving a more consistent operation and improved finishes. Another effect was significant reduction in glazing of the honing stones. When cutting surfaces became dull, vibrations aided in fracturing the abrasive grains, thus exposing new cutting edges.

A small, portable, ultrasonic tool was also developed for deburring holes and slots, for example. Since the fatigue strength of the burr is considerably less than that of the body of material, the ultrasonic tool was capable of "working" the burr rapidly, loosening and removing it, with no damage to even the most delicate part.

199. Balamuth, L., "Ultrasonic Vibrations Shape Metals." SAE Journal, Vol. 71, July 1963, p. 36-41.

Ultrasonic vibration of a honing stone as it rotated about its axis was said to have two major advantages over conventional honing: Because of the

high forces present at an ultrasonically vibrating interface, the operation was performed with minimum pressure; thus the operation was more consistent and resulted in improved surface finish. Also, the vibrations eliminated or greatly reduced glazing of the honing stones by ultrasonic fracture of the abrasive grains, thus dressing the stone.

200. Walker, W. F., "Ultrasonics in Production Processes." Ultrasonics, Vol. 1, July 1963, p. 123-129.

Ultrasonic deburring was not considered practical to replace shot blasting or tumbling, but was well suited to removing small, hard burrs or sharp edges from parts having a small radius. Two processes were being used: immersion of the components in an abrasive slurry in a deburring chamber with a transducer mounted at its base, which produced surface finish of 15-20 µin.; and use of a shaped cutting tool attached to the transducer, working in abrasive slurry to bombard the parts, producing surface finish of 10-15 µin. The latter process was said to be suitable for deburring large quantities of components having only a small, hard burr or difficult to deburr with other techniques.

201. Balamuth, L., "Recent Developments in Ultrasonic Metalworking Processes." SAE Paper 849G, Air Transport and Space Meeting, New York, April 27-30, 1964. Also Balamuth, "Ultrasonic Metalworking." American Machinist, Vol. 108, April 13, 1964, p. 136-138.

In ultrasonic lapping and honing, cutting was achieved by the action of loose or fixed abrasive grains, excited to relatively low peak velocities, and with low gross motion of the work relative to the lap or hone. The superior surface finish and minimal subsurface damage was attributed to this low velocity. In ultrasonic lapping of steel and other metals, the rate of material removal was about three times that achieved without ultrasonics.

202. Ishmukov, G. I., "Lapping Holes with Ultrasonic Vibration of the Tool." Russian Engineering Journal, Vol. 46, Sept. 1966, p. 79-81.

To increase productivity in finishing precision holes, lapping of 10-mm-diameter holes in chrome steel was carried out with axial oscillation of the tool at 18-22 kHz. Removal rate for achieving the same precision finish increased with vibratory frequency and amplitude, was less affected by lap speed, and decreased with increasing clearance between lap and work. Tool wear was rapid, and it was suggested that the workpiece rather than the tool be oscillated.

Finishing

203. Goodman, E. and W. B. Czechanski, "Surface Finishing of Fine Beryllium Wire." Tech. Report AFML-TR-67-274, Value Engineering Co., Alexandria, Va., Air Force Contract AF 33(615)-5368, Sept. 1967.

A process was developed for finishing 0.005-in. beryllium wire which had been drawn in nickel cladding. The process utilized electrochemical etching in a potassium chloride/nitric acid solution in the presence of 25-kHz ultrasonic energy to remove the nickel, followed by chemical milling in an acid solution in the presence of ultrasonics to impart a smooth surface finish. Ultrasonics in the electrochemical process increased the rate of nickel removal and increased the limiting current density. The finished wire demonstrated increased tensile and yield strength, increased ductility, and increased elastic modulus over wire processed by other methods. In a prototype production setup, 50,000 feet of wire was processed without replenishing the acid solutions.

204. Hurst, T., "Vibratory Deburring 24-Ft Wing Spars." Industrial Finishing, Vol. 47, April 1970, p. 38-41.

A large vibratory deburring machine, operating at high frequency and low amplitude, was constructed for deburring 24-ft spars, and permitted tripling the output while reducing the number of finishing personnel by two-thirds. The same equipment was used for deburring smaller parts in hundreds per load. It served also to clean and degrease the parts. Where one aircraft part once required 20 min to debur by hand, 50 pieces per machine load were deburred in a 2-hr cycle, saving 15-18 min per part. A plastic medium with quartz abrasive was used.

D. METAL JOINING

General

205. Silin, L. L., The Application of Ultrasonics in Welding and Casting Processes. VINITI, Moscow, 1959. (U. S. Dept. of Commerce Translation 62-24713)

Results were presented of work in the Soviet Union and elsewhere on ultrasonic application to fusion welding to modify weld structure, improve mechanical and thermal properties of welded joints, and reduce crack formation; to resistance welding to refine cast structure; and ultrasonic welding per se. It was noted that ultrasonics can not replace other welding methods, but it broadens the potentialities of welding processes.

206. Fridman, V. M., Ultrasonics. USSR, undated. (Air Force Translation MCL-1298, Sept. 18, 1961)

This comprehensive review of ultrasonic applications in industrial use or being considered for industrial use includes discussions on ultrasonic soldering and tinning and ultrasonic welding, apparently the only two metal-working processes considered to have commercial potential. Various types of equipment for these purposes were described.

207. Gellert, R., "Vibrations--New Aid to Joining." SAE Paper 650761, National Aeronautics and Space Engineering and Manufacturing Meeting, Los Angeles, Oct. 4-8, 1965. Also Gellert, "Ultrasonic Vibrations Help Join Metals." SAE Journal, Vol. 74, July 1966, p. 48-49.

Discussion of the nature and capabilities of ultrasonic metal joining included a review of ultrasonic welding, ultrasonic soldering, and ultrasonically assisted fusion welding. The wide variety of metals that can thus be joined permits the designer to use the best metals for the job, not those best suited to available welding processes. It was not suggested that conventional techniques be abandoned, but that ultrasonic techniques be investigated where other methods fail.

208. Hauser, R. L. and R. E. Fisher, "Ultrasonics Boost Strength, Speed Cure of Adhesives." Materials Engineering, Vol. 67, April 1968, p. 76-77.

Ultrasonic vibration, transmitted to the interface between mating parts, was found to speed the cure of many adhesives and increase bond strength. In addition to melting or curing the adhesive, the mechanical agitation forced adhesive into porous materials and cleaned the surface of nonporous ones. Adhesives responding to ultrasonic activation were said to be solution and emulsion types, hot-melt adhesives and copolymers, and fast-curing (B-stage) thermosetting types. Used primarily for joining nonmetallic materials, the process was also effective for joining metals to themselves or to nonmetals.

209. Heinkel, E., "Supersonic Spot Welding." FD 3025/49 (probably British Intelligence Objectives Sub-Committee report), 1949. (PB 105439).

Information from Germany mentioned briefly the invention of an ultrasonic spotwelding apparatus which produced weld spots having the same texture as the unwelded, unheat-treated material surrounding it. The process was proposed for aircraft surfaces to eliminate the use of rivets.

210. Jones, J. B. and C. F. DePrisco, "The Application of Ultrasonic Energy to Cold Welding of Metals." Research Report 53-77, Aeroprojects Inc., Army Contract DA-36-034-ORD-1007, Nov. 1953.

Equipment was devised and experiments carried out in ultrasonic spot welding of 0.005- and 0.010-in. aluminum sheet at room temperature, with vibrations introduced normal to the sheet surface. Adequate weld strength was obtained with no external deformation of the workpieces, although internal deformation of the faying surfaces was present. The welds showed no corrosion effects after 2000 hours exposure in salt water or hot distilled water. Preliminary experiments indicated that other metals could be ultrasonically welded.

211. Jones, J. B., C. F. DePrisco, and J. G. Thomas, "Ultrasonic Welding of Aluminum." AEC Report DP-107, Aeroprojects Inc., Feb. 1955.

Continued development of the ultrasonic welding process led to improved weld strength in 1100 aluminum and good solid-phase bonding as revealed in metallographic examination. No corrosion effects on the welds were noted after 5 months exposure to salt or hot distilled water, and no effects of thermal cycling up to about 250°C. The process was demonstrated to be feasible for joining small aluminum ribs to aluminum surfaces.

212. Jones, J. B., C. F. DePrisco, and J. G. Thomas, "Ultrasonic Welding of Metals." Research Report 55-30, Aeroprojects Inc., Army Contract DA-36-034-ORD-1403, April 1955.

Ultrasonic welding of metals was found to be most effective with vibrations introduced parallel rather than normal to the weld interface. Successful welds were achieved in 1100 aluminum in gages up to 0.062 in., as well as in thin gages of other metals and alloys. No strength reduction was evident after 5000 hours exposure to corrosion environments. Surfaces films adversely affected weld strength, and best results were achieved with polished surfaces.

213. Jones, J. B., C. DePrisco, and J. G. Thomas, "Ultrasonic Welding of Metals for Ordnance Application." Research Report 56-14, Aeroprojects Inc., Army Contract DA-36-034-ORD-1665, March 1956.

Refinements in ultrasonic welding systems resulted in significant improvements in welding capability. Excellent bonds were obtained in four tempers of cartridge brass in gages up to 0.016 in. Weld area increased with increasing sheet thickness and with increasing clamping force. Other metals such as aluminum, copper, gilding metal, and low-carbon steel showed similar increase in weld area with sheet thickness. The use of varied cleaning methods appeared to have no effect on weld strength. A continuous-seam ultrasonic welder was developed and shown to be practical in joining aluminum foil up to 0.005 in. thick.

214. Jones, J. B. and J. J. Powers, "Ultrasonic Welding." Welding Journal, Vol. 35, Aug. 1956, p. 761-766.

Ultrasonic welding was noted to be a solid-state bonding process for both similar and dissimilar metals, accomplished without application of external heat. The workpieces are clamped at low pressure between two sonotrodes and ultrasonic energy is introduced for a brief interval. The operating variables are static force, ultrasonic power, and weld time. Frequencies in the range of 4 to 40 kHz have been used. The mechanism of ultrasonic welding was said to be related to stress distribution, net energy delivered, and temperature developed in the weld zone, as well as to the properties of the material being welded. Immediate applicability to joining foil or thin sheet to either thin or massive members, or small ribs to flat sheet and to cylindrical tubes, was indicated.

215. Aeroprojects Inc., "Feasibility Investigation of Ultrasonic Welding as a Means for Joining Heat Exchanger Components." Research Report 56-50, Oct. 1956.

Ultrasonic spot welds in 316 stainless steel and Inconel in sheet gages from 0.005 to 0.020 inch showed strengths substantially exceeding MIL-W-6858 specifications for resistance spotwelds, and strength scatter was low. Seam welding of stainless steel panels to corrugated sheets was carried out using a special welding tip and clamping arrangement. After thermal treatment, strength testing resulted in fracture of the parent metal rather than shearing of the weld.

216. Brackmann, W., R. Levinsohn, and D. McCarthy, "Basic Considerations in Foil Transformer Production." Electrical Manufacturing, Vol. 59, Jan. 1957, p. 94-99.

Ultrasonic welding was successfully used for attachment of aluminum and copper ribbon-type leads to transformer coils, replacing troublesome soldering

or resistance welding operations. No preweld cleaning was required and joints could be made even through insulation.

217. Jones, J. B., C. F. DePrisco, and J. G. Thomas, "Attachment of Spiral Ribs to Aluminum Tubes by Ultrasonic Welding." AEC Report DP-168, Aeroprojects Inc., Jan. 1957. Also Jones, DePrisco, and Thomas, "Ultrasonic Techniques Applied to Fuel Element Fabrication and Processing." AEC Report DP-199, Feb. 1957.

Ultrasonic welding equipment and techniques were developed for bonding aluminum ribs in a spiral configuration to the outside surface of aluminum tubing by overlapping spot welds spaced 12 to the inch. The equipment was automated so that a rib could be attached to a 17-ft tube in about 2 hrs. Subsequently, an ultrasonic continuous-seam welder was used to produce rib-to-plate welds at rates two to four times faster and with strengths equivalent to those produced with the spot welder.

218. Collins, F. R. "Ultrasonic Welding." Report 2-57-5, Process Metallurgy Div., Aluminum Research Labs., Aluminum Co. of America, New Kensington, Pa., Feb. 25, 1957.

Ultrasonic welding was used to join aluminum to itself and to other metals in thicknesses ranging from 0.00025 to 0.064 in. Such welds generally had shear strengths essentially the same as the parent metal and exhibited nugget tear-out on testing. The weld was characterized by severe disturbance of the faying surface, partial obliteration of the interface, and no heat-affected zones or intermetallic compounds. Proposed applications included electrical joints, sealing of foil containers, and transition joints.

219. Jones, J. B. and E. E. Weismantel, "Ultrasonic Joining." Proc. Second RETMA Conf. on Reliable Electrical Connections, Philadelphia, Sept. 11-12, 1956, p. 97-103. Also Jones and Weismantel, "Ultrasonic Metal Joining." Electrical Manufacturing, Vol. 59, April 1957, p. 125-129.

Ultrasonic welding was said to be useful for joining electrical materials such as aluminum, copper, and silver when one member was in the range of 0.00015 to 0.040 in. thick. Bimetallic welds were possible and practical, preweld cleaning was not critical, and welding was accomplished through anodized coatings and certain types of plastic coatings. The equipment offered flexibility for production use, since the driving power source could be located remote from the welding head, and power requirements were lower than for resistance welding.

220. Aeroprojects Inc., "Attachment of Windshields to AP Shot by Ultrasonic Welding." Research Report 57-60, Army Contract DA-36-034-ORD-96, July 1957.

Conical steel windshields were ultrasonically welded to AP and TP shot using 3 to 24 spot welds per assembly. The force-power-time relationship was not optimized because of the limited power capability of existing welders. With equipment delivering 2000-3000 watts power, it appeared that the welds could be produced in 1.5 sec or less. Some heat effects were observed in the shot in the vicinity of the welds.

221. Jones, J. B. and E. E. Weismantel, "Ultrasonic Welding of Structural Aluminum Alloys." Research Report 57-13, Aeroprojects Inc., Navy Contract NOas 56-161-c, Jan. 1957. Also Jones and F. R. Meyer, "Ultrasonic Welding of Structural Aluminum Alloys." Welding Journal, Vol. 37, March 1958, p. 81s-92s.

Ultrasonic welds in 1100-H14, 2024-T3, and 7075-T6 aluminum alloys in thicknesses ranging from 0.051 to 0.081 in. demonstrated shear strengths meeting or exceeding the requirements of MIL-W-6860 for resistance spotwelds. The process was effectively supplemented with low-temperature heat. Continuous-seam welds were also shown to be feasible. Preweld cleaning was indicated to be less critical than for aircraft-quality resistance spotwelding.

222. Jones, J. B., "Ultrasonic Welding--A New Technique Grows." Metal Progress, Vol. 73, April 1958, p. 68-71.

Several types of ultrasonic welders were described: a laterally driven reed type for high power levels, a lateral-drive type for low powers (below about 300 watts), and continuous-seam welders wherein a rotating transducer-coupling system transmits vibratory energy to a roller disk tip. The mechanism of ultrasonic welding and metallography of typical welds were described. Strength data were provided for welds in stainless steel, Inconel, titanium alloys, and Zircaloy-2. Strengths in 17-7 PH stainless steel, for example, in gages up to 0.020 in., exceeded MIL-W-6858 specifications for resistance welds in this material.

223. Mommsen, J. T., "Ultrasonic Welding of Ribs for Projection Fuel Elements." AEC Report HW-51911, Hanford Atomic Products Operation, Richland, Wash., April 28, 1958.

The ultrasonic welding of small solid aluminum ribs, 0.120 in. high by 0.150 in. wide by 1-1/16 in. long, to cylindrical fuel elements was accomplished using a welding tip designed to straddle the rib and weld through both base flanges simultaneously. Overlapping spot welds, 16 to the inch, were used to

bond the entire undersurface of the rib. Successful welds were produced which failed in shear by fracture of the rib rather than shearing of the bond. Corrosion flow tests showed no localized corrosion in the vicinity of the ribs, although water had gained access to the underside of some ribs where unbonded areas were noted.

224. Weber, W., "Ultrasonic Welding." Werkstatt und Betrieb, Vol. 91, June 1958, p. 305-310. (In German)

The author reviewed the status of ultrasonic welding, including discussions of some of the basic problems in delivering vibratory energy to the workpiece, the apparatus and operating variables, the mechanism, including temperature relationships, relationships to material properties, and areas of application.

225. Kitaigorodskii, Y. I., M. G. Kogan, V. A. Kuznetsova, N. N. Rykalin, and L. L. Silin, "Joining of Metals in Solid State by Ultrasonic Vibration." Izvestiya Akademii Nauk SSSR, Otdelenie Tekhnicheskikh Nauk, Metallurgiya i Toplivo, 1958, No. 8, p. 88-90. (Brutcher Translation 4401)

The USSR Academy of Sciences investigated ultrasonic spot welding of aluminum, copper, and stainless steel in thicknesses up to 1.5 mm and established the dependence of weld quality on material properties, such as hardness, plasticity, surface condition, and thickness, and on operating conditions such as vibratory amplitude, weld time, contact force, and tip geometry. Welds produced under suitable conditions failed by parent metal fracture. Metallographic examination showed characteristic whorls in the weld zone with some metals and gradual transition between components in other metals.

226. Rienks, F., "Feasibility Study on Ultrasonic Welding of 5086-H34 Aluminum Alloy." Final Summary Report, Phase A, Gulton Industries, Inc., Metuchen, N. J., Army Contract DA-30-069-ORD-2302, Sept. 1958.

Ultrasonic welding of aluminum alloy was undertaken with a view to field repair of skins of ballistic missiles. Major efforts involved the development of welding equipment, especially tips, reflectors, and force systems. With the best system evolved, welds in 0.050-in. and 0.063-in. 5086-H34 aluminum alloy showed joint efficiencies in the range of 35-48%. With 0.125-in. material, joint efficiency was 16-20%. Welding times were in the range of 6 to 60 seconds.

227. Ol'shanskiy, N. A., A. V. Mordvintseva, and M. N. Krumboldt, "The Use of Ultrasonics in Seam and Spot Welding." Avtomaticheskaya Svarka, 1958, No. 10, p. 75-80. (Library of Congress Translation 60-15654)

Equipment for ultrasonic spot and seam welding was described and strength data provided for spot welds in aluminum up to 1.5 mm thick. Temperature measurements showed the maximum temperature developed in copper was 600°C and in aluminum 400°C. Seam welds were stronger than spot welds and failed by fracture of the parent metal.

228. Jones, J. B. and W. C. Potthoff, "Ultrasonic Welding Techniques." Tech. Paper 152, American Society of Tool Engineers, Vol. 58, Book 2, Oct. 1958.

Typical applications for ultrasonic welding include welding small ribs to rods, bridgewire assemblies, heat exchanger components, stainless steel strainer material, stranded aluminum wire to copper terminals, and waffle-type sandwich structures. Spot and seam welding systems were described and several types of welding tip geometry illustrated. Typical weld strengths for a variety of materials were tabulated, and the progress in increasing the range of weldable sheet thicknesses with the development of higher power equipment was

229. Jones, J. B. and F. R. Meyer, "Further Development in Ultrasonic Welding of Structural Aluminum Alloys." Research Report 58-35, Aeroprojects Inc., Navy Contract NOas 57-580-c, Oct. 1958. Also Jones and W. C. Potthoff, "Certain Structural Properties of Ultrasonic Welds in Aluminum Alloys." Welding Journal, Vol. 38, July 1959, p. 282s-288s.

Ultrasonic spot-type welds in structural aluminum alloys in gages up to about 0.090 inch were superior in shear strength to MIL-W-6858A requirements for resistance spotwelds and equivalent in cross-tension strength. Ultrasonically joined specimens of 2024-T3 Alclad showed superior fatigue strength under high-load, low cycle conditions and at least equivalent strength under low-load, high-cycle conditions. The weldability of bare aluminum alloys was improved by inclusion of an aluminum foil interleaf between weldment members. Ultrasonic joining of thicker alloys was said to be contingent on development of higher power welding equipment.

230. McCarthy, D., V. Pirc, and W. Hannahs, "Ultra-Sonic Welded Aluminum-Copper Junctions as Electrical Connections." Third Electronics Industries Assoc. Conf., Dallas, Texas, Dec. 1958.

Ultrasonic welding was determined to be an effective means for attaching aluminum ribbon leads 0.00025 to 0.0005 in. thick to copper transformer coils 0.002 to 0.0028 in. thick. Good weld strength was obtained even through

insulating coatings. The electrical conductivity of the ultrasonic joints was equivalent to that of capacitor discharge welds and markedly superior to soldered joints after 14,000 hours of operation. The ultrasonic method was noted to lend itself to automation, since no liquids, fluxes, or external heat were required.

231. Wirt, J. R., "What About Ultrasonic Welding?" Midwest Welding Conference, Chicago, Jan. 28-29, 1959. Also Wirt, "Ultrasonic Welding: Theory and Practice." Industry and Welding, Vol. 32, April 1959, p. 38-39.

Description and illustrations were provided for ultrasonic spot welders having capacities from 100 watts to 4000 watts. Representative photomicrographs showed intergranular penetration and plastic flow at the weld interface but no changes in metallurgical structure and no intermetallic formations, as illustrated by welds in copper, Zircaloy-2, stainless steel, and Inconel, and bimetallic welds joining various combinations of these materials and others.

232. Weare, N. E., J. N. Antonevich, R. E. Monroe, and D. C. Martin, "Research and Development of Procedures for Joining of Similar and Dissimilar Heat-Resisting Alloys by Ultrasonic Welding." WADC Technical Report 58-479, Battelle Memorial Institute, Air Force Contract AF 33(616)-5342, Feb. 1959. Also Antonevich and Monroe, "Ultrasonics and Welding." Battelle Technical Review, Vol. 8, March 1959, p. 9-13. Also Weare and Monroe, "Ultrasonic Welding of Heat-Resisting Materials." Welding Journal, Vol. 40, Aug. 1961, p. 351s-358s.

Research in the mechanism of ultrasonic welding indicated heat generation at the weld interface, apparently due to friction, and a thin molten film was believed to be formed at the interface. Equations were developed to relate material properties, ultrasonic welding conditions, and required interfacial temperatures. Power requirements were found to increase with increased material thickness and hardness. Welds in titanium, molybdenum, stainless steel, niobium, and Inconel generally contained cracks at the edges of the weld area, due apparently to high alternating stresses which induced fatigue failure.

233. Potthoff, W. C. and H. L. McKaig, "Ultrasonic Welding Survey Report and Ultrasonic Welding Equipment Manual." Research Report 59-106, Aeroprojects Inc., Navy Contract NOas 58-108-c, May 1959.

A survey of 11 major Defense suppliers indicated interest in ultrasonic welding for joining high-temperature and high-strength materials in the aircraft and missile industries, for joining dissimilar metals for both structural and electronic applications, for combinations of metals and non-metals, and for a range of electronic applications. It was recommended that high-power spot and seam welding equipment be developed and that military specifications covering at least a few basic materials be developed as a pattern for

a broad range of similar and dissimilar metal combinations. Available types of ultrasonic spot welders and their capabilities were described.

234. Jones, J. B., N. Maropis, J. G. Thomas, and D. Bancroft, "Fundamentals of Ultrasonic Welding, Phase I." Research Report 59-105, Aeroprojects Inc., Navy Contract NOas 58-108-c, May 1959. Also Jones, Maropis, Thomas, and Bancroft, "Phenomenological Considerations in Ultrasonic Welding." Welding Journal, Vol. 40, July 1961, p. 289s-305s.

Investigation resulted in special instrumentation and techniques for observing and interpreting ultrasonic welding phenomena, including stress distribution in the weld zone, vibratory energy delivered and transmitted through the weld zone, temperatures developed in the weld zone, material properties and their relation to weldability, and interface disturbance and metallurgy.

235. Koziarski, J., "Some Considerations on Design for Fatigue in Welded Aircraft Structures." Welding Journal, Vol. 38, June 1959, p. 565-575.

Ultrasonic welding was noted to offer unusual possibilities for the design of fatigue-resistant structures: The size of the weld nugget is not limited by sheet thickness as in resistance welding; minimum edge distance is not critical; in some instances more reliable joints are produced; no special surface preparation is required; foil can be welded to itself or to thick sheets; dissimilar metals can be welded together; difficult-to-weld metals can be joined; no melting of the weld metal occurs, hence shrinkage stresses are low; surface indentation is negligible (<5%); power requirements are lower than for resistance welding. More development is required to achieve the full potential of this process.

236. Collins, F. R., "Properties of Aeroprojects Ultrasonic Seam Welds." Report 2-59-14, Process Metallurgy Div., Alcoa Research Labs., Aluminum Co. of America, New Kensington, Pa., Aug. 7, 1959.

Ultrasonic seam welds in various tempers of 1100, 3003, and 5154 aluminum alloys in gages from 0.006 to 0.025 in. showed good strength and reproducibility. Joint efficiency in lap welds was close to 100% for thin gages, but decreased to about 65% in 0.025-in. material. All welds showed good metallurgical bonding and no evidence of melting. The welds were produced with power levels up to 1800 watts and at welding rates up to 7.5 ft/min.

237. Jones, J. B. and L. D. Barrett, "Ultrasonic Welding of Aluminum Alloys for Missile Use." Research Report 59-84, Aeroprojects Inc., Army Contract DA-36-034-ORD-2424, Aug. 1959; Supplement, RR 60-8, Feb. 1960. Also G. D. Johnston, "Hydrostatic Pressure Test of Ultra-Sonically Welded Cylinders Made of 2014-T6 Aluminum." Report DSF-TN-1-59, Army Ballistic Missile Agency, Huntsville, Ala., Jan. 14, 1959.

Equipment, techniques, and design data for joining structural aluminum alloys (2024-T6, 5086-H34, and 2014-T6) for missile use were developed. Single and overlapping spot welds and continuous-seam welds were evaluated for leaktightness, strength, joint efficiency, and ductility. Joint efficiencies as high as 92% were obtained with spot welds in 0.064-in. 2014-T6 alloy. With the thicker materials, an aluminum foil interleaf improved weld strength. Good continuous-seam welds were achieved in 0.032-inch material.

238. Collins, F. R., J. D. Dowd, and M. W. Brennecke, "Ultrasonic Welding of Aluminum." Welding Journal, Vol. 38, Oct. 1959, p. 969-975.

Ultrasonic welding was found to produce strong welds in aluminum alloys in gages ranging from 0.00025 in. to 0.125 in. In annealed aluminum, the welds were as strong as resistance welds; in cold-worked and heat-treated sheet, the ultrasonic welds were stronger. No surface preparation was required except for removal of heavy heat-treating scale. Welding conditions of power, force, and time were found to require careful adjustment for each material, temper, and gage.

239. London, G. J., "Ultrasonic Welding of Molybdenum and Tantalum." Report R59S452, General Electric Missile and Space Vehicle Dept., Philadelphia, Air Force Contract AF04(647)-269, Oct. 29, 1959.

The applicability of ultrasonic welding for joining molybdenum and tantalum in gages up to 0.010 in. was demonstrated. Spot-type welds in the thicker material showed an average strength of 199 pounds for molybdenum and 270 pounds for tantalum. Observations indicated the possibility of bulk recrystallization during welding. An adhesion theory of surface interaction was postulated as accounting for weld formation.

240. Winter, J. and J. P. Neilsen, "Preliminary Study on the Mechanics of Ultrasonic Welding." New York University, College of Engineering, Div. of Research, Nov. 1959.

It was proposed that any one or combination of four mechanisms may be responsible for ultrasonic welding: melting at the interface, mechanical interlock, interfacial atomic forces, and/or interfacial chemical reaction. These speculations were deduced from metallographic studies of ultrasonic bonds of similar and dissimilar metals.

241. Hopkins, J. S., "Ultrasonic Welding of Thin Molybdenum Sheet." Report WEST A-2664, Westinghouse Electric Corp., Dec. 28, 1959.

Ultrasonic welding should be ideally suited to fabrication of sheet metal components of molybdenum, since the process involves solid-state

joining and the welds contain no cast structure or heat-affected zones. Preliminary experimentation in welding commercially pure and 0.5%-Ti molybdenum sheet indicated potential advantages.

242. Ainbinder, S. B., "Certain Problems in Ultrasonic Welding." Welding Production (USSR), 1959, No. 12, p. 10-18.

Calculations and experiments showed a considerable temperature rise in the weld zone and indicated that ultrasonic welding is a type of pressure welding at high temperatures approaching the melting point, occurring from friction between the components. In order for such welding to take place, surface films must be removed in the contact zone and the surfaces must be brought into close contact so that interatomic forces will act.

243. Sirotyuk, M. G., "Transformation of Longitudinal Acoustic Oscillations into Shear or Torsional Oscillations." Soviet Physics--Acoustics, Vol. 5, 1959, p. 259.

An apparatus for converting acoustic longitudinal oscillations into shear or torsional oscillations consisted of a metal waveguide with slotted helical grooves gradually deepening and diminishing in spacing toward the output end. This end therefore produced large-amplitude torsional waves. This concentrator was used for welding 0.1-mm aluminum sheets together in about 1 sec, with a strength of several kilograms.

244. Ol'shanskiy, N. A. and A. V. Mordvintseva, "Ultrasound in Welding Technique." Industrial Use of Ultrasound, Gosudarstvennoye Nauchno-Tekhnicheskoya Izdatel'stvo Maschinostroitel'noy Literatury, Moscow, 1959, p. 287-302. (Air Force Translation MCL-810)

The advantages of ultrasonic welding were said to include absence of melting, low electrical power requirements, low thickness deformation, less critical pre-weld cleaning, possibility of welding thin to thick sheet or stack welding, and applicability to high-melting metals. Several types of spot and seam welders were described and illustrated and their mode of action in producing vibratory displacement stresses in the weld zone was discussed.

245. Krumboldt, M. H., "Spot Welding with the Help of Ultrasound." Monograph, Leninzdat, 1959, p. 235-243. (Air Force Translation MCL-811)

Studies were made of the temperature rise during ultrasonic welding of several materials, using chromel-alumel thermocouples installed in the weld joint. In all cases the temperature showed a sharp initial rise followed by a leveling off. Extended welding time, up to 4 min, showed a peak temperature after 40-60 sec, with a maximum of 300°-400°C for aluminum and 500°-600°C

for copper. Strength tests on welded joints showed ultrasonic welds to be as strong as resistance welds.

246. Jones, J. B., "Ultrasonic Welding." Fabrication of Molybdenum, American Society for Metals, Cleveland, Ohio, 1959, p. 88-102.

After a discussion of ultrasonic welding systems, including the necessity for force-insensitive mounting systems to minimize energy loss and frequency shift under applied loads, and of representative applications, observations were made on metallurgical and thermal phenomena in ultrasonic welds, including low thickness deformation, turbulent disturbance at the interface, phase transformation, and recrystallization. Temperature rise data for several materials were presented. Special attention was given to the weldability of high-temperature and refractory metals and alloys.

247. Friske, W. H., "Interim Report on the Aluminum Powder Metallurgy Product Development Program." Report NAA-SR-4233, Atomics International, Canoga Park, Cal., AEC Contract AT(11-1)-GEN-8, Jan. 15, 1960.

Ultrasonic welds were successfully produced in aluminum powder metallurgy products, including M257 and M486 in 0.032-in. thickness. In peel tests at room temperature and at 800°F, failure occurred in the parent metal rather than in the weld.

248. Jones, J. B. and H. L. McKaig, "Ultrasonic Welding and Improved Structural Efficiency." Paper 60-10, 28th Annual Meeting, Institute of Aeronautical Sciences, New York, Jan. 25-27, 1960.

Data were provided to substantiate the good strength and reproducibility of ultrasonic welds in several aircraft structural materials, exceeding values considered satisfactory for aircraft applications. Studies showed that such factors as edge distance, spot spacing, and row spacing were not critical as in resistance welding. Both overlapping-spot seams and continuous seams provided high-strength leak-tight joints of 80 to 100% efficiency under pressure tests. Essentially no degradation of material properties occurred even with a 100% span weld (produced with overlapping spots).

249. Pocalyko, A., "New Advancements in Ultrasonic Welding." Proc. American Ordnance Assoc., Watertown Arsenal, Mass., Feb. 9-10, 1960, p. 7-14.

Ultrasonic welding was observed to find increasingly wider use in industry, with such applications as joining ribbon-wound pressure vessels, ring welding of cone-core structures, hermetic sealing and packaging, and encapsulation of bridgewire assemblies. Advances in equipment and techniques, including use of statistical quality control methods, have provided welds of high integrity

and extremely high reliability. Capabilities were said to be limited primarily by the power capacity of available equipment. The desirability of obtaining data for development of military specifications covering the process was emphasized.

250. Antonevich, J. N., "Ultrasonic Welding Equipment." IRE Trans. on Ultrasonic Engineering, Vol. UE-7, Feb. 1960, p. 26-32.

Fundamental studies in ultrasonic welding indicated the process to be a form of pressure or friction welding in which materials clamped together are welded when made to slide in contact with each other, a process related to the frictional phenomena of galling and seizing. The basic components of welding equipment and operating parameters were discussed. Indications were that practical butt, spot, and seam welders could be designed but would generally be limited in application to thin-gage materials.

251. Potthoff, W. C., J. G. Thomas, and F. R. Meyer, "Ultrasonic Welding of Dissimilar-Metal Combinations." Welding Journal, Vol. 39, Feb. 1960, p. 131-138.

Ultrasonic welding was being used for joining dissimilar metal combinations difficult or impractical to weld by conventional methods. Such welds were generally free from interdiffusion, intermetallic compounds, and brittleness that often characterize fusion welds. Many combinations of high-temperature refractory metals and alloys of particular interest for aircraft, missiles, and rockets have been effectively joined, as well as electrical connections of excellent conductivity with combinations of aluminum, copper, silver, and other materials.

252. Silin, L. L., V. A. Kuznetsov, and G. V. Sysolin, "The Ultrasonic Welding of Aluminum and Its Alloys." Welding Production (USSR), 1960, No. 3, p. 19-25.

Investigation was made of the effect of several variables on ultrasonic spot weld strength: contact pressure, weld time, vibratory amplitude, and frequency in several aluminum alloys in thickness up to 1.6 mm. For pressure, time, and amplitude, there were optimum values at which shear strength was maximum.

253. Welkowitz, W., "Ultrasonic Welder Design Considerations." Electronic Industries, Vol. 19, May 1960, p. 106-109.

This article describes significant factors in the design of ultrasonic welding systems, including transducer design, mechanical design, and driving amplifiers. Seam welds were said to be possible by overlapping spots, rolling the tool over the work, and dragging the tool over the work. Suggested mechanisms for ultrasonic welding were mentioned.

254. Lewis, W. J., J. N. Antonevich, R. E. Monroe, and P. J. Rieppel, "Fundamental Studies in the Mechanism of Ultrasonic Welding." WADD Technical Report 60-607, Battelle Memorial Institute, Columbus, Ohio, Air Force Contract AF 33(616)-6268, June 1960.

Fundamental studies related to ultrasonically welding heat-resistant materials showed weld strength to be proportional to the strength of the base material, unaffected by surface cleanliness, and unaffected by mass. Cracking frequently occurred at the periphery of the weld and could not be eliminated by welding in a vacuum or preheating. Temperatures in the weld zone were estimated to reach 1800°-2000°F in these alloys. The usefulness of ultrasonic welding for heat-resistant alloys was believed to be of doubtful value.

255. Balandin, G. F. and L. L. Silin, "On the Role of Friction When Welding with Ultrasound." Izvestiya Akademii Nauk SSSR, Otdelenie Tekhnicheskikh Nauk, Metallurgiya i Toplivo, 1960, No. 6, p. 42-46. (Air Force Translation MCL-1045/1)

Studies of temperature variations and distributions during ultrasonic welding indicated that heating is caused by friction, primarily between the weldment components, and also between welding tip and upper component. Initially this friction disrupts surface films at the interface, then intensive plastic flow occurs in this area after relative displacement ceases. A temperature maximum was recorded at the instant the frictional effects ceased; this should be considered the minimum welding time.

256. Noltingk, B. E., "Ultrasonic Welding." Welding and Metal Fabrication, Vol. 28, July 1960, p. 260-265.

Experiments were conducted to throw light on the basic mechanism of ultrasonic welding. Weldability was found to be dependent on the weldment material and thickness. Aluminum was most readily welded, followed by copper. Surface condition was not important, and welds were made through thin films of polythene or paint or anodizing. The mechanism was said to involve abrasion at the interface to break up surface films, heat generation through frictional forces, and softening and deformation of the metal to allow a continuous metal path across the interface. Areas requiring further development and investigation were discussed.

257. Silin, L. L., V. A. Kuznetsov, and M. A. El'yashev, "The Joint Strength of Ultrasonic Welds in Aluminum Alloys." Welding Production (USSR), 1960, No. 7, p. 8-14.

Shear strengths of ultrasonic welds in 0.8- and 1.2-mm aluminum alloy sheet were 30% higher than resistance weld strengths when tested at both room and elevated temperatures, but greater strength variability occurred with

ultrasonic welds. It was suggested that greater strength could be obtained with automatic frequency control and by increasing the power introduced into the weldment.

258. Jones, J. B., "Welding Aluminum, Copper and Stainless Steel With Ultrasonics." Metal Progress, Vol. 78, July 1960, p. 117-120.

In a study of the relationship between material properties and ultrasonic weldability, substantially greater power per unit area was required to weld 302 stainless steel over a range of gages than for copper, and the requirement for copper was greater than for 1100-H18 aluminum. The weld strengths achieved showed the same relationship. Metallographic characteristics of welds in similar and dissimilar combinations of these materials were discussed.

259. Koziarski, J. and J. C. Balston, "Ultrasonic Welding Review of Available Tensile-Shear Data." Project Report D-74, Manufacturing Research and Development, Martin Co., Denver, Colo., Aug. 3, 1960.

Available data on ultrasonic welding of a range of materials, including aluminum, steel, copper, nickel, titanium, molybdenum, zirconium, and beryllium and their alloys, in both similar and dissimilar combinations, were reviewed and summarized. In nearly all instances, shear strengths were higher than those of conventional spotwelds. In order to use ultrasonic welding in space or missile applications, it was recommended that design criteria, process specifications, and quality control criteria be developed.

260. Weare, N. E., J. N. Antonevich, and R. E. Monroe, "Fundamental Studies of Ultrasonic Welding." Welding Journal, Vol. 39, Aug. 1960, p. 331s-341s.

Ultrasonic welding data indicated bonding to be due to the presence of a thin molten film in the interface, although definite proof of this mechanism was not obtained. Mathematical equations based on friction were derived to express the important factors involved. Experiments were conducted to determine the effect of several variables on weld quality. Within limits, weld strength increased with increased tip displacement, weld time, and clamping force and was not affected by tip radius or surface conditions. With increasing thickness, higher power was required to effect good welds.

261. Spears, R. K., "Evaluation of Ultrasonic Welding." Report Q85.20.00.-00-F3-01, Martin Co., Denver, Colo., Nov. 1, 1960.

Ultrasonic welding was examined for several applications in the aircraft and missile industry, including: stainless steel to aluminum, copper wire to

printed circuit boards, thermocouples to various materials, copper wires to copper terminal posts, copper terminals to structural materials, welding of Iridited aluminum and of surface-treated magnesium-thorium. In most instances sound joints were achieved, but welds involving coated materials were inferior. Welds in sheet materials exceeded resistance spotweld specifications, and wire welds failed at strengths equivalent to those of the parent metals.

262. Fabel, G. W., "Ultrasonic Welding: Optimizing the Variables." Assembly and Fastener Engineering, Vol. 3, Nov. 1960, p. 32-36.

The variables involved in ultrasonic welding were stated to be tip geometry, frequency, power, time, and clamping force, and each type of weldment has its own set of optimum conditions that will apply. Experimentation is therefore required in each instance; a rather complex procedure was proposed for establishing particularly time, force, and power.

263. Terrill, J. R., F. R. Collins, and J. D. Dowd, "Applications for Ultrasonic Welding of Aluminum." Paper 60-WA-322, American Society of Mechanical Engineers, New York, Nov. 27-Dec. 2, 1960.

Many unique applications of ultrasonic welding were attributed to the capability for welding difficult combinations such as foil to foil or foil to plate or dissimilar metals by spot or continuous-seam welding. Suggested applications included building panels, aluminum mufflers and other automobile assemblies where dissimilar metals must be joined, and other structural uses. Advantages and problems of ultrasonic welding were discussed. Higher capacity and lower cost equipment were said to be required for extension of its usefulness.

264. Combustion Engineering, Inc. and Aeroprojects Inc., "A Program to Study the Feasibility of and Develop an Apparatus for the Ultrasonic Roll Bonding of Fuel Plates." Report CEND-93, AEC Contract AT(30-1)-2379, Dec. 1960.

Ultrasonic weld-cladding of plate-type fuel elements was accomplished by overlapping seam welding at spacings in the range of 0.100-0.115 in. Edge rail bonding was achieved with a roller tip having a grooved periphery to match the edge rail. Blister formation at the interface that occurred during testing to 900°F was eliminated with higher power equipment that permitted faster welding speeds.

265. Jones, J. B., N. Maropis, J. G. Thomas, and D. Bancroft, "Fundamentals of Ultrasonic Welding, Phase II." Research Report 60-91, Aeroprojects Inc., Navy Contract NOa(s) 59-6070-c, Dec. 1960.

Photoelastic studies showed ultrasonic welds to be initiated as a result of vibration-induced shear stresses combining with normal stresses to produce islands of local slip within an area of elastic strain. Sheet thickness and Vickers microhardness were combined to permit approximation of energy required to produce welds. Bonds were often characterized by internal deformations without significant external deformations. Recrystallization sometimes occurred but not always. Weld temperatures were found to fall in the range of 35-50% of the absolute melting temperature. There was no evidence of melting in any monometallic weld.

266. Potthoff, W. C. and W. N. Rosenberg, "Ultrasonic Welding in Production." Proc. American Power Conference, Vol. 22, 1960, p. 700-706.

Ultrasonic equipment and applications, particularly those in the electrical industry, were reviewed, and the advantages for production processing were delineated: simple operating controls which include only time, power, and clamping force; initiation and completion of the welding cycle usually by depressing a foot switch; accommodation of various materials and thicknesses on the same welder; amenability to statistical quality control; reduced installation and operating costs because of lower power requirements; remote location of power source to relieve congestion of production lines; and low maintenance.

267. Jones, J. B. et al., "Ultrasonic Welding." Welding Handbook, Section Three, Fourth Edition, American Welding Society, New York, 1960, Chapter 52; Fifth Edition, 1965, Chapter 49; Sixth Edition, 1971, Chapter 59.

These presentations, prepared by committees of experts in ultrasonic welding and periodically updated, cover all facets of this joining technique, including fundamentals of the process, weldable materials, welding techniques, weld characteristics, quality control, characteristics and types of equipment, and applications.

268. Ol'shanskii, N. A., "On the Joining of Metals by Ultrasonic Welding." Avtomaticheskaya Svarka, 1961, No. 3, p. 3-11. (Brutcher Translation 5463).

Ultrasonic welding was attributed to friction between the workpieces, with high temperatures and deformation playing secondary roles. The friction eliminates oxide films and contaminants and exposes clean surfaces that are capable of seizing; pressure brings the clean surfaces into contact so that interatomic binding forces can act. Surface finish does not affect bond strength but determines the power required for welding. Wire brushing of the surface improves weldability.

269. Koziarski, J., "Ultrasonic Welding: Engineering, Manufacturing and Quality Control Problems." Welding Journal, Vol. 40, April 1961, p. 349-358.

Ultrasonic welding was considered to offer substantial potential, for example in aircraft design where the ability to join certain components would effect substantial savings. The necessity to educate the designer was emphasized, as was the need to establish design allowables, manufacturing specifications, and quality control criteria. More powerful and more flexible equipment should be developed to satisfy present and future needs.

270. Allen, C. H. and G. Miller, "An Ultrasonic Welding Machine for Attaching Supports to Reactor Fuel Elements." AEC Report HW-69461, Hanford Atomic Products Operation, Richland, Wash., May 1, 1961. Also E. V. Padgett, "An Ultrasonic Welding Process for Attaching Aluminum Support Rails to Cylindrical Aluminum Clad Hanford Fuel Elements." HW-70938, Sept. 5, 1961.

One of the first successful applications of ultrasonic welding to heavy-duty production was the attachment of small rails to reactor fuel elements. The equipment operated semi-automatically, with an operator required only to place the rails in a feeder and push the feeder button. An operator could attach rails to 200 fuel elements per hour, producing 2400 welds on 1200 rails. Equipment and procedures were described in detail.

271. Koziarski, J., "Ultrasonic Welding Joins Stainless to Aluminum in Nuclear Power Plant." Materials in Design Engineering, Vol. 53, May 1961, p. 146-147.

The SNAP-1A reactor incorporated an inner skin of 321 stainless steel and an outer skin of 6061-T6 aluminum alloy which required hermetically tight joints. This was satisfactorily accomplished by ultrasonic overlapping-spot welds at a spacing of 18-20 per in. The joints showed strengths approximating the aluminum alloy parent metal strength, and successfully withstood 30-40 psig air pressure and 1 atm helium pressure without leaking.

272. Alden, J. H., "Ultrasonic Sealing of Foil." Modern Packaging, Vol. 34, July 1961, p. 129-133.

The development of ultrasonic roller seam welding for splicing aluminum foil in rolling mills to repair breaks or produce longer lengths was described. The previously used embossing or crimping made a conspicuous splice of low strength, and adhesive bonding required high operator skill to obtain a good joint. Successful ultrasonic splices were made in foils 0.00017-0.003 in. thick with strengths in excess of 90% of the parent metal strength and scarcely detectable in subsequent processing. Such equipment was installed in all Alcoa foil mills.

273. Jones, J. B., H. L. McKaig, and J. G. Thomas, "Investigation of Ultrasonic Welding of All-Beta Titanium Alloy." Research Report 61-77, Aeroprojects Inc., Navy Contract NOw-60-0643, Sept. 1961.

Ultrasonic spot welding was established as feasible for fabricating structural members from thin strips of titanium alloy. Successful multi-ply structures were assembled by both through-welding and ply-by-ply ultrasonic welding techniques. This offered the possibility of achieving structural assemblies of high strength but lighter in weight than those of steel or other special alloys currently in use.

274. Fabel, G. W., "Instrumenting the Ultrasonic Welder." Assembly and Fastener Engineering, Vol. 4, Oct. 1961, p. 37-40.

A reliable system was devised for monitoring frequency changes in an ultrasonic welding device. This resonance indicator incorporated signal lights to alert the operator. Design and operation of the systems was described. The technique was said to be an improvement over unreliable observation techniques or complex oscilloscope monitoring.

275. Balandin, G. F. and L. L. Silin, "Methods for Obtaining Steady Conditions in the Ultrasonic Welding of Metals." Welding Production (USSR), 1961, No. 12, p. 1-9.

Study was made of the thermal cycle, variation in vibratory amplitude, and structure of the joint in ultrasonic welding. Maximum temperature was found to be associated with maximum weld strength. It was recommended that for strong weld joints, vibratory losses should be kept to a minimum by suitable selection of tip material and condition, and that operating conditions be carefully selected, especially to achieve constant vibratory amplitude and frequency.

276. Jones, J. B., N. Maropis, C. F. DePrisco, J. G. Thomas, and J. Devine, "Development of Ultrasonic Welding Equipment for Refractory Metals." Report ASD TR 7-888(II), Aeroprojects Inc., Air Force Contract AF 33(600)-43026, Dec. 1961.

Projections were made to establish power requirements and equipment necessary for joining refractory metals and alloys in thicknesses up to 0.10 in. in both mono- and bimetallic combinations. The studies were supplemented by new data obtained with an 8-kw laboratory welder which permitted joining such materials up to 0.040 in. thick. Pertinent information on transducer, coupler, and tip materials was ascertained experimentally, and specifications for a 25-kw machine were delineated.

277. Lehfeldt, W., "Ultrasonic Welding." Industrie-Anzeiger, Vol. 83, Feb. 28, 1961, p. 251-254. Also Lehfeldt, "Ultrasonic Welding of Aluminum." Aluminium (Berlin), Vol. 37, 1961, p. 226-230. (In German)

The construction and mode of operation of ultrasonic spot and seam welders were described. Typical applications mentioned were joining of aluminum and of dissimilar metals, electrical connections, packaging, and the electronics industry. Advantages for each type of application were noted. The process was said to offer a useful extension of previously known welding processes.

278. Warren, L., "Ultrasonic Welding." Report MR1275, 52X SV61, Lockheed Missiles and Space Co., Sunnyvale, Cal., 1961.

Ultrasonic welding investigations with a variety of materials revealed that: Aluminum was probably the most readily weldable material; aluminum was readily welded to coated magnesium; titanium foil welds showed good joint strength but with some evidence of cracking; Inconel X was successfully joined to itself; refractory metal welds showed severe cracking at the weld edges; aluminum screen wire was welded to transparent plastic. The process was considered to have potential for missile applications, and further exploration was recommended to establish its range of applicability and to develop production weld quality criteria.

279. Ross, E. G., "Response Surface Techniques as a Statistical Approach to Research and Development in Ultrasonic Welding." 1961 ASQC Convention Trans., American Society for Quality Control, p. 445-456.

Statistical design of experiments, statistical analysis of data, and routine quality control have been applied to ultrasonic welding to differentiate between operating conditions (time, force, power) that produce high-quality welds and those producing defective or cracked welds with wide strength variability. Techniques for applying such statistical procedures were described.

280. Ol'shanskiy, N. A. and M. N. Krumbol'dt, "Ultrasonic Spot-Welding of Aluminum Alloys." Vyssheye Tekhnicheskoye Uchilishche, Trudy, 1961, No. 101, p. 49-99. (Air Force Translation FTD-TT-123/1)

This document presents a comprehensive survey of the history of ultrasonic welding, the principles for construction of ultrasonic welders, the effect of various parameters such as tip material and geometry, power, force, time, preweld cleaning, etc. on weld strength and microstructure, and the effect of use environment. It is concluded that for some materials ultrasonic welding can replace resistance welding, and in some cases ultrasonic welding is the only method that can be used.

281. Fischer, G., "Ultrasonic Welding Machines." Mécanique Electricité, Paris, Jan. 1962.

A review of ultrasonic welding included the designs and capabilities of spot and seam welding equipment commercially available in France, Germany, United States, and the Soviet Union. The equipment was said to be particularly applicable for assembling light alloy components for aircraft and space vessel capsules as a replacement for resistance welding.

282. Koziarski, J., "Ultrasonic Welding--Phase II and IV, Joining and Attaching Thermocouples." Project Report D-89, Martin Company, Denver, Colo., Sept. 8, 1961. Also J. Cwik, "Thermocouple Attachment by Ultrasonic Welding--Phases V and VI." Project Report D-94, Feb. 23, 1962.

Ultrasonic welding was established as a practical and economical means for making accurate thermocouple joints and installations, increasing sensitivity and providing a joining medium that did not affect metallic structure. In many applications it provided the only solution. Results proved the advantages and reliability of the process. The development of a portable ultrasonic welder for this application was recommended.

283. Savchenko, B. V., "The Effect of Surface Preparation Methods on the Quality of Ultrasonic Welding." Welding Production (USSR), 1962, No. 3, p. 14-20.

The effect of surface films on ultrasonic weld strength in aluminum alloys and the effects of various type of surface treatment were investigated. Using techniques which removed oil and other adsorbed contaminants but had no substantial chemical action on oxide films, weld strength was increased by 30-50%. The deliberate introduction of oil on the surfaces substantially reduced weld strength since it changed the friction conditions on the surfaces. Pickling of the material after degreasing gave only a minor strength increase and was considered to offer little advantage.

284. Bruk, M. V., "Distribution of Oxide Films in Contact Area During Ultrasonic Welding." Avtomaticheskaya Svarka, 1962, No. 3, p. 54-57. (Brutcher Translation 5574)

Studies indicated that oxide films on surfaces of metals being ultrasonically welded are first broken up in the contact area as a result of contact pressure, then are removed under the action of predominately tangential forces and concentrate at the periphery of the weld spot. The clean surfaces then come into contact and are metallurgically joined under the action of plastic deformation. Experiments demonstrated the feasibility of welding aluminum alloys through an anodized layer.

285. Rhines, F. N., "Study of Changes Occurring in Metal Structure During Ultrasonic Welding." Summary Report TP 82-162, Metallurgical Research Lab., University of Florida, Gainesville, April 1962.

Studies were made of the mechanics of ultrasonic welding and the response of metals to ultrasonic excitation. Observed phenomena in the weld nugget were attributed to plastic shearing involving a 10-20% decrease in yield stress of all the metal subjected to vibration and additional localized flow in the weld nugget reducing it to a quasi-liquid state, associated with increase in dislocation density. The two halves of a weldment could be rotated with respect to each other during the ultrasonic pulse, and there was occasional extrusion of metal from between the faying surfaces; at the end of the ultrasonic pulse, the metal again became resistant to deformation, and excess dislocations were believed to cancel out.

286. Aeroprojects Inc., "Ultrasonic Weldcladding of Flat-Plate Fuel Elements." Report NYO-10456, AEC Contract AT(30-1)-1836, June 1962.

Techniques and equipment were developed for ultrasonic bonding of aluminum alloy cladding to aluminum-uranium core material. Core faces were clad by overlapping seam welds, and edge cladding with multiple layers of thin foil appeared promising. Equipment development led to a 2-kw seam welder which accomplished face cladding at a rate of about 20 $in.^2$/min. Extrapolation to a 5-kw welder indicated a fuel plate 8 ft by 4 in. could be clad on both sides in 5-7 min.

287. Aeroprojects Inc., "Development of Ultrasonic Welding with Emphasis on Producing Hermetic Seals." Research Report 62-48, Army Contract DA-36-034-ORD-3254RD, Aug. 1962.

Uniformly reproducible ultrasonic ring and continuous-seam welds of hermetic-seal quality were produced in several alloys of various gages and geometries. Seam welds were produced at rates greater than 1 ft/min in 0.064-in. 2014-T6 aluminum alloy, and weld strengths were up to 95% of parent metal strength. Higher power equipment was projected, and impedance-matching requirements for optimum coupling into the weldment materials were investigated.

288. Savchenko, B. V. and V. A. Kuznetsov, "The Ultrasonic Welding of Honeycomb Structures." Welding Production (USSR), 1962, No. 9, p. 34-36.

Hexagonal honeycomb sections were fabricated from corrugated strips of 0.1-mm-thick aluminum alloy by spot welding in the flat areas between the corrugations. Elongated spots produced higher strengths than round spots. Hexagonal rods were inserted to give rigidity to the structure during welding. With the light-gage material, no precleaning of the surfaces was necessary. The process was proposed for production use.

289. Zolotarev, B. B., Y. D. Volkov, and V. I. Domaskin, "The Ultrasonic Spotwelding of Metals." Welding Production (USSR), 1962, No. 9, p. 65-73.

It was noted that the principal factor hindering large-scale adoption of ultrasonic welding was the inconsistent quality of the welded joints. Weld strength in a variety of metal and alloys was found to be affected by such factors as tip surface condition and geometry, anvil material, shape, and surface finish, and surface condition of the workpieces. It was concluded that the joining mechanism must be further investigated and weld quality indices established before the process can effectively be used for load-carrying joints.

290. Ainbinder, S. B. and E. K. Tikhomirova, "The Mechanism Whereby Joints are Formed in Ultrasonic Welding." Welding Production (USSR), 1962, No. 9, p. 61-65.

As a result of metallographic examination of ultrasonic welds in aluminum and copper, it was postulated that the constant normal load and varying tangential load in the weld zone break up and remove oxide films, and the associated temperature rise makes possible a metallurgical bond. When this has occurred, dissipation of energy in the weld zone decreases and external friction becomes internal friction. With continued ultrasonic application, fatigue fracture in the joint may occur.

291. Gelles, S. H., "Beryllium Research and Development Program." Report ASD-TDR-62-509, Vol. 1, Nuclear Metals, Inc., and Aeroprojects Inc., Air Force Contract AF 33(616)-7065, Oct. 1962.

Investigations to determine the ultrasonic weldability of beryllium sheet material indicated the maximum weldable sheet gage at 4-kw power input to be approximately 0.020 in. Welding machine settings and welding tip material and geometry were investigated. Use of aluminum foil interleaf in the weld zone eliminated beryllium cracking tendencies. Best welds were obtained with sheet material that was smooth, flat, and free from surface defects. Power-force programming was suggested as a means for further improvement.

292. Ol'shanskii, N. A., "Ultrasonic Welding of Anodized Duralumin D16AT and Alloy SAP." Welding Non-Ferrous Alloys and Certain Alloy Steels, Symposium, Moscow, 1962, p. 84-92. (In Russian)

Ultrasonic welding of 0.5-mm and 1.0-mm sheets of SAP alloy and anodized Duralumin yielded joints which possessed good strength at both room and elevated temperature. Study of weld microstructure and temperature in the weld zone showed ultrasonic welding of these alloys to be similar to cold welding.

293. Okada, M. and S. Shin, "Study on Ultrasonic Welding." Journal of Japan Welding Society, Vol. 32, Jan. 1963, p. 14-31; Feb. 1963, p. 38-51. (In Japanese)

Study was made of the factors influencing heat generation in ultrasonic welding: power, tip pressure, joining time, materials to be joined, and sheet thickness. Temperature measurements in aluminum, titanium, and copper showed temperature rises greater than 700°C. Joinability was improved by electrolytic polishing of the material to be joined and by insert material. Further work showed the joining of various copper alloys and of zirconium or titanium to stainless steel to be feasible.

294. Aeroprojects Inc., "Ultrasonic Welding of Selected Refractory Metals and Alloys." Research Report 63-54, Navy Contract NOw 61-0410-c, June 1963.

Investigations with thin gages of molybdenum and niobium alloys and tungsten showed that these materials were susceptible to ultrasonic welding, and that the strength decay of such welds at 2000°F was not appreciably greater than that of the parent material. Weld cracking tendencies were attributed primarily to material contamination and to non-uniform material quality. It was suggested that improved weld quality could be obtained by strict control of material quality and by use of programmed ultrasonic power and clamping force.

295. Beckert, M. and J. Wodara, "Ultrasonic Welding of Aluminum to Copper." Schweisstechnik, Vol. 13, Aug. 1963, p. 377-380. (In German)

The interrelationships of weld time, clamping force, and power in welding aluminum to copper were investigated. Weld strength generally increased with increase in weld time, power, and force up to a point, beyond which strength usually showed a decrease. Metallographic studies showed little or no interdiffusion between the metals but rather a mechanical interpenetration. The process was recommended as a replacement for soldering aluminum and copper.

296. Okada, M., S. Shin, M. Miyagi, and H. Matsuda, "Joint Mechanism of Ultrasonic Welding." Trans. Japan Institute of Metals, Vol. 4, Oct. 1963, p. 250-256. (In Japanese)

Examination of the microstructure of ultrasonic welds between copper and titanium showed neither a mechanical interlock nor formation of intermetallic compounds at the interface. In view of the observed temperature rise, it appeared that atomic bonding occurred. X-ray microanalysis indicated diffusion of copper atoms into the titanium and vice versa.

297. Alov, A. A. and W. Baier, "Some Problems Regarding the Formation of Joints Welded With Ultrasonic Vibrations." Avtomaticheskaya Svarka, 1963, No. 11, p. 66-71. (Brutcher Translation 6151)

Ultrasonic welding studies in copper and aluminum alloy showed rapid breakdown of oxide films and their distribution throughout the mass of deformed metal. The metal in the contact zone was noted to enter a quasi-liquid state during welding and become solid again as soon as the ultrasonics was switched off. Welds made with stepped clamping force were about 15% stronger than welds made with constant force.

298. Maropis, N. and J. G. Thomas, "Ultrasonic Welding of Refractory Metals and Alloys with Power-Force Programming." Research Report 63-66, Aeroprojects Inc., Navy Contract NOw 63-0125c, Dec. 1963.

Equipment was assembled for ultrasonic welding with power-force programming, which provided incremental changes in ultrasonic power and clamping force during a single weld interval. Significant strength improvement was obtained in welding aluminum alloy and Inconel, as well as molybdenum and niobium alloys.

299. Okada, M., S. Shin, M. Miyagi, and H. Matsuda, "Joint Mechanism of Ultrasonic Welding." Trans. Japan Institute of Metals, Vol. 4, 1963, p. 250-256.

Microscopic and X-ray diffraction studies on ultrasonic similar and dissimilar metal welds revealed recrystallization structure but no evidence of intermetallic compounds or other phases. The temperature rise at the weld interface was substantially greater than that at the tip-workpiece interface. In copper-titanium joints, interatomic diffusion was found to occur. Age-hardenable alloys developed high weld strengths due to the acceleration of diffusion of solute atoms under ultrasonic influence.

300. Munford, J. A., B. R. Cantor, and A. Piltch, "Ultrasonic Welding of a Beryllium Window Assembly." NASA Tech. Memorandum X-935, Goddard Space Flight Center, Greenbelt, Md., Jan. 1964.

Thin beryllium window assemblies in rigid frames were fabricated by ultrasonically ring welding thin (0.001 in.) beryllium foil to 310 stainless steel frames with an interleaf ring of 0.001-in. aluminum foil. Leaktight joints were obtained, although there was some spalling in the vicinity of the land, attributed to the poor quality of the beryllium used.

Solid-State Welding

301. Ulery, W. E., R. F. Johnson, and C. Fugue, "A Limited Evaluation of Ultrasonic Spot Welds in X2020-T6 Aluminum Alloy Sheet." Report A461, McDonnell Aircraft Corp., St. Louis, Mo., Air Force Contract 33(657)-11215, March 10, 1964.

Ultrasonic spot welds in X2020-T6 aluminum alloy were found to be stronger than resistance spot welds in the same material. It was observed that more comprehensive test work should be done to qualify this process for manufacture of production parts of various structural alloys.

302. Nippes, E. and J. B. Jones, "Metals Joining in the Space Age--4. By Ultrasonics." Journal of Metals, Vol. 16, March 1964, p. 244-245.

The versatility of ultrasonic welding in joining a wide variety of materials, particularly the space age materials, was discussed and representative photomicrographs illustrated. Of particular significance were experiments in joining thoria-dispersed nickel, 0.025 in. thick, with joint efficiencies in the vicinity of 78%. Strength tests at 2000°F showed about the same strength degradation for the welds and for the base material. Effort directed toward automated assembly equipment and procedures should make this technique more useful.

303. Ol'shanskii, N. A. and A. V. Mordvintseva, "Ultrasonics in Welding." Ultrasound in Industrial Processing and Control, Soviet Progress in Applied Ultrasonics, Vol. 1, Mashgiz, Moscow, 1959, p. 58-68. (Translation: Consultants Bureau, New York, 1964)

Ultrasonic spot and seam welding equipment was described, fundamentals of the process were discussed, and the effects of time and compressive force on weld quality were examined.

304. Nishio, Y., Y. Yamamota, Y. Fukaya, and M. Masushige, "Study on Lining Titanium to Steel by Application of the Special Welding Method." Technical Review, Mitsubishi Heavy Industries, Ltd., Japan, Jan. 1965, p. 23-33.

Two techniques were found effective for lining titanium to steel vessels for the chemical industry: resistance welding with a silver alloy insert, and ultrasonic welding with an aluminum insert. Either method could replace mechanical joining, which requires a greater titanium thickness than the welding techniques.

305. Krumboldt, M. N., "Joining Electric Motor Windings to the Commutator Segments by Ultrasonic Welding." Welding Production (USSR), 1965, No. 1, p. 50-52.

Ultrasonic welding was found suitable for joining windings to commutator segments for high-speed fractional-horsepower electric motors, replacing the previously used cumbersome brazing operation. When welded with insulation removed, the welds showed reproducibly good strengths and low electrical resistance. Several hours exposure at 160°C did not significantly degrade the joints.

306. Aeroprojects Inc., "Development of Ultrasonic Ring Welding Techniques for Fabrication of Oil Cooler Tube-to-Header Assemblies." Research Report 65-39, Navy Contract N600(19)-61902, March 1965.

Ultrasonic welding of aircraft oil cooler tubes to header plates was accomplished by ring welding and by cylinder welding. Ring welding required flaring the tubes and welding them to holes in the header plates. In cylinder welding, a longitudinally vibrating welding tip traversed the inside periphery of the unflared cooler tubes. Weld strengths produced by both methods were approximately equal. The cylinder welding approach appeared more practical.

307. Maronna, G. and B. Weiss, "Survey of Ultrasonic Welding." Schweisstechnik, East Berlin, Vol. 15, April 1965, p. 167-171. (In German)

Ultrasonic spot, seam, and butt welding was observed to be effective with materials not joinable by the usual methods, such as dissimilar metal combinations, and foils to thick members. The strength of ultrasonically welded joints was about 15% higher than that of resistance welds. Copper could be joined to steel without removing insulation coatings. Molybdenum could be joined to itself at weld times below 2 sec to prevent crack formation. Niobium was joined to high-strength steel in 1 sec.

308. Zglenicki, C., "Ultrasonic Welding." Product Engineering, Vol. 36, Feb. 15, 1965, p. 87-91. Also Zglenicki, "Pros and Cons of Ultrasonic Welding." Metalworking Production, Vol. 109, May 19, 1965, p. 68-72.

Compared with other types of welding, such as fusion, electron beam, resistance, and cold pressure welding, ultrasonic welding is useful for joining a wider range of dissimilar metals, although the thickness range is more restricted; cleaning is less critical than for most other processes; there is no heat-affected zone and no distortion; the process is fast. This technique was said to be most effective and most economical for materials difficult or impossible to join by other methods.

309. Neppiras, E. A., "Ultrasonic Welding of Metals." Ultrasonics, Vol. 3, July 1965, p. 128-135. Also Neppiras, "Ultrasonic Welding of Metals and Plastics." Summer Conf., Engineering Materials and Design Assoc., Brighton, England, July 5-7, 1966.

Ultrasonic spot, seam, and ring welding equipment and techniques were reviewed, together with the range of applications in the electronics, packaging, electrical engineering, and structural engineering fields. Special advantages were noted to be the ability to weld thin sheet and foil of dissimilar metals as well as thin to thick members, speed in making seam and ring welds in foils, absence of gross distortion of the materials, adaptability to a wide range of joint designs, lack of dependence of bond strength on surface cleanliness, and the very restricted zone of high temperature.

310. Kagan, Y. I., V. P. Neonet, A. A. But, and V. M. Shkil', "Ultrasonic Welds Between Leads Insulated With Lacquer or Enamel." Welding Production (USSR), 1965, No. 8, p. 49-53.

Single and multi-core copper cables over the entire range of sizes used in the electrical industry were welded to each other without removal of enamel or lacquer insulation. With aluminum cables in sizes below about 1 mm, the insulation must first be removed. Static strength of the weld was 75-90% of that of the unwelded cable, and electrical resistance was more than 85% of the unwelded cable value.

311. Constantine, L. S., "Development of Methods to Improve Corrosion Behavior of Threaded Fastener Installations in Aluminum Alloys." Report NAEC-AML-2258, U. S. Naval Air Engineering Center, Philadelphia, Sept. 10, 1965.

Using an environmental corrosion test chamber developed to obtain accelerated exfoliation-type corrosion, representative of service in an aircraft carrier environment, specimens containing countersunk fastener heads coated with an epoxy system and similar fasteners "capped" with ultrasonic ring welding were exposed for 3 weeks and then fatigue tested at 15,000 lb. The coated specimens failed at 5500 and 8300 cycles, while the ring-welded specimens lasted to 15,000 cycles. Microscopic examination showed intergranular attack on the epoxy-coated specimens and no such attack on the welded specimens. The ultrasonic ring welding technique was recommended for further development. (See Ref. 314)

312. Daniels, H. P. C., "Ultrasonic Welding." Ultrasonics, Vol. 3, Oct. 1965, p. 190-196.

Ultrasonic spot welding equipment was described and the mutual dependence of variables of pressure, power, and weld time was surveyed. Power requirements were said to depend on the thickness and hardness of the material

being welded. Surface cleaning was not considered necessary but was sometimes recommended for reproducibility of weld quality. Particular applications were noted to be welding of sheets of similar or dissimilar metals, welding of wires to themselves or to other components, and welding of metals to nonmetals.

313. Vernon, C. W. J., "Ultrasonic Welding." Welding and Metal Fabrication, Vol. 33, Nov. 1965, p. 438-445.

The acceptance of ultrasonic welding in European countries was noted, and British manufacturers were said to be producing equipment. The design and construction of various types of units and typical applications were described. The immediate future for the process was said to lie in fields involving thin sheet, foil, and wire; with higher power units, it could possibly be competitive for thicker gage materials.

314. Aeroprojects Inc., "Ultrasonic Ring Welding of Hermetic Covers Over Fastener Heads on Aircraft Surfaces." Research Report 66-58, Navy Contract N165-47064, June 1966.

The feasibility of installing covers over aircraft fasteners by ultrasonic ring welding, in order to protect the aluminum skin/steel bolt interface from corrosive atmosphere, was demonstrated. A spot-facing tool was aligned with the welder to provide the flat surface required for welding. All seals were helium leaktight at a sensitivity of 10^{-9} cm^3/sec. Test panels were prepared to simulate the processing used on an aircraft wing.

315. Kuznetsov, V. A. and L. L. Silin, "'In-Process' Quality Control of Ultrasonic Welds." Welding Production (USSR), 1966, No. 10, p. 10-17.

It was discovered that weld quality could be monitored during formation by the amplitude of vibrations transmitted through the weld into the anvil. When the oscillator was switched off at a given signal strength level, the shear force values were constant within ± 5%. With time control, values were constant within ± 5% if the components had the same initial surface condition. At similar values of tool penetration, strength scatter did not exceed ± 8%. Equipment was developed for such in-process control.

316. Jones, J. B., "Ultrasonic Welding in 1966." Tech. Report C6-3.1, 1966 National Metals Congress, American Society for Metals, Chicago, Oct. 31-Nov. 3, 1966.

Ultrasonic welding was said to be making progress in industrial applications because of the low temperature generated at the weld interface and the capability for welding unusual metallic combinations and geometries. Industrial applications have been stimulated by recent developments in ceramic

transducers and solid-state frequency converters, which increase equipment efficiency and compactness while decreasing complexity and cost. Typical applications included ring-weld encapsulation, foil splicing, joining of foil to thick plate, welding can body side seams, and various electronic applications. The process was being used in automatic and semi-automatic production lines.

317. Maropis, N., "Development of Ultrasonic Welding Equipment for Refractory Metals." Report AFML-TR-66-351, Aeroprojects Inc., Air Force Contract AF 33(600)-43026, Nov. 1966.

Ultrasonic spot welding equipment consisting of a highly stable, precisely adjustable motor-alternator frequency converter of 25-kw output, ceramic transducers exhibiting efficiencies of 75-85%, and heavy-duty force-insensitive coupling systems was developed and used in welding refractory metals and superalloys. The equipment provided for programming power and force applied to the weldment to improve impedance match. Ultrasonic welds were made with this equipment in materials and thicknesses not previously weldable.

318. Apanasenko, V. F., "Aluminum Welded with High-Frequency Ultrasonic Vibrations." Automatic Welding (USSR), 1967, No. 3, p. 88-89.

Experiments were conducted in ultrasonic welding of aluminum 0.8 mm thick at a frequency of 2 MHz, using treatment times varying from 3 to 60 sec and temperatures up to 600°C. Good welds were achieved with appropriate welding conditions. This was suggested as a means for welding thick materials, since dissipation losses are less at higher frequencies.

319. Gencsoy, H. T., J. A. Adams, and S. Shin, "On Some Fundamental Problems in Ultrasonic Welding of Dissimilar Metals." Welding Journal, Vol. 46, April 1967, p. 145s-153s.

Studies in ultrasonic welding of thin gages of low-carbon steel, stainless steel, and zirconium indicated that bond formation could be attributed to shattering of the oxide film at the interface allowing nascent metal contact through interatomic diffusion. An aluminum foil interleaf improved weldability of these materials. In constructing threshold curves, it was found that tip sticking and fatigue occurred when energy and force levels were too high.

320. Ginzburg, S. K. and Yu. G. Nosov, "Features of the Diffusion Processes in Technical Iron During Ultrasonic Welding." Metallovedenie i Termicheskaya Obrabotka Metallov, 1967, No. 4, p. 59-60. (Brutcher Translation 7195)

In ultrasonic spot welding of iron, intensive carbon diffusion occurred, leading to the appearance of slack-quenched regions. The findings were explained either by initial heating of the local regions to 1100°C or higher, or by heating to lower temperatures and acceleration of diffusion by the ultrasonic treatment.

321. Jones, J. B., "Ultrasonic Welding." Proc. CIRP International Conf. on Manufacturing Technology, Ann Arbor, Mich., Sept. 25-28, 1967, p. 1387-1410.

This paper included discussions of the basic requirements of ultrasonic welding systems, weld energy requirements, system efficiency, fundamental relationships in the process, equipment design, and representative applications. The latter included joining of metallic foils and dissimilar metals, low-temperature applications, unusual weld geometries involving ring or line welds, electronic and electrical connections, fuel element fabrication, foil splicing, and can body side seams. A broader range of applications was predicted within the foreseeable future.

322. Pfaelzer, P. F. and J. Frisch, "Ultrasonic Welding of Metals in Vacuum." Final Report MD-67-3, College of Engineering, University of California, Berkeley, Dec. 1967.

The ultrasonic weldability of copper was substantially increased by welding in a vacuum of 10^{-10} torr. The coefficient of adhesion, as determined by weld fracture tests, was practically doubled at low input power levels and increased manyfold at higher power levels. In the vacuum welds, the central portion of the weld showed uniform adhesion, while welds produced in air have low adhesion in this area. It was concluded that the superior strength of vacuum welds was due to non-slip of the components and that gross sliding induces a stress-cycle-dependent fatigue failure.

323. Ginzburg, S. K., "Formation of the Joint in Ultrasonic Welding." Welding Production (USSR), 1967, No. 5, p. 83-87.

In an effort to obtain information on the mechanism of ultrasonic welding, welds were made in copper at high values of amplitude and low unit pressures and also at low amplitudes and high pressure. The latter was observed to produce stronger welds. It was concluded that the zones of initial seizure (asperities) become harder and build up, then lose hardness because of diffusion of point defects from the welding zone, promoted by reciprocating deformations and heating of the metal.

324. Shin, S. and H. T. Gencsoy, "Ultrasonic Welding of Metals to Nonmetallic Materials." Welding Journal, Vol. 47, Sept. 1968, p. 398s-403s.

Ultrasonic spot welds were made between low-carbon steel and several nonmetals such as glass, polyethylene, polypropylene, and acrylic, using an aluminum foil interleaf. In all cases, the welding tip contacted the steel. Materials which were greatly deformed and softened during welding presented some difficulties. Welding of metals to plastics was considered an ion bonding process, and metals to glass appeared to involve atomic or interatomic diffusion bonding.

325. Heyman, E. and G. Pusch, "Recrystallization During the Formation of a Joint in Ultrasonic Welding." Schweisstechnik (Berlin), Vol. 19, Dec. 1969, p. 542-545. (Brutcher Translation 8153)

Metallographic and x-ray crystallization studies of ultrasonic welds in copper and iron specimens failed to reveal recrystallization phenomena. A quality weld was always accompanied by heavy plastic flow and turbulence involving both metal components. As a result of the plastic flow, surface impurities were broken up and clean surfaces brought together to within atomic distance so that cohesive forces became effective. The role of diffusion could not yet be explained.

326. Hazlett, T. H. and S. M. Ambekar, "Additional Studies on Interface Temperature and Bonding Mechanisms of Ultrasonic Welds." Welding Journal, Vol. 49, May 1970, p. 196s-200s.

In an effort to determine the temperature rise in ultrasonic welding, welds were made between iron-constantan and copper-constantan couples. Recorded temperatures were low, in the range of 300°-350°F, and were attributed to the combined effects of elastic hysteresis, plastic deformation, and interfacial friction. On the basis of scanning electron micrographs, some bonds were attributed to mechanical mixing at the interface and nascent metal contact, some to nascent metal bonding alone, and some to grain-boundary diffusion across the interface.

327. Estes, C. L., "Practical Applications for the Ultrasonic Welding Process." Document Y-DA-3555, Union Carbide Corp., Nuclear Div., Oak Ridge, Tenn., June 26, 1970.

Ultrasonic ring welding successfully sealed temperature-indicating capsules containing low-melting Cerro alloys, used to indicate environmental temperatures experienced by lunar sample return containers. Pinch welding of aluminum tubes produced reliable hermetic seals. A steel filter screen was ring-welded to a steel ring, and a retaining ring having scalloped outer edges was ring-welded to a diaphragm. The decision to use ultrasonic welding for

a specific application requires consideration of the advantages and limitations of the process. Justification of investment in ultrasonic welding equipment depends on unit production cost savings, production rates, and material savings.

328. Frisch, J. and U. Chang, "Optimal Strength of Ultrasonically Bonded Metals in Air and Vacuum." Final Report MD-70-2, College of Engineering, University of California, Berkeley, Sept. 1970.

Experiments in ultrasonic welding of 2024-T351 aluminum alloy and OFHC copper indicated that the mechanism was primarily solid-state bonding (adhesion, mechanical interlocking, recrystallization, and possibly diffusion). Both interfacial slip and sublayer plastic deformation occurred, and relative displacement was necessary to achieve these conditions. Excessively high power inputs or large vibratory amplitudes deteriorated weld integrity by overstressing and/or fatigue cracking. A vacuum environment did not significantly improve weld strength in the aluminum alloy.

329. Nefedov, V. V. and Yu. V. Kholopov, "The Ultrasonic Seam Welding of Foil." Automatic Welding (USSR), 1970, No. 12, p. 58-60.

Ultrasonic seam welding of aluminum up to 2 mm thick was investigated at welding speeds of 1-5 m/min, and variations of weld strength as a function of frequency, welding rate, and contact force were determined. An optimum welding rate was established for a given contact force. At the slower speeds, weld strength was increased with increasing clamping force. At speeds above about 3 m/min, strength decreased with increasing clamping force. The process was considered a productive method of joining aluminum, copper, nickel, and other metal foils.

330. Hauser, D., D. G. Howden, and R. E. Monroe, "Diffusion Bonding of Metal Munition Containers." Final Tech. Report, Battelle Memorial Institute, Columbus, Ohio, Army Contract DAAA15-70-C-0255, Jan. 1971.

Several solid-state bonding processes were considered for hermetically sealing chemical-filled metal munition containers. Ultrasonic ring welding was concluded to be one of the most promising because little surface cleaning is required, it is adaptable to high production rates, dissimilar metal combinations can be joined, and no cast structures are formed. Experimental evaluation of this technique was recommended but was not carried out because of sheet thickness limitations.

331. Sigma Design Co. (Irvington, N. J.), "A Study of Feasibility to Automatically Assemble Components Using Ultrasonic Welding Technique." Tech. Report, Army Contract DAAA21-71-C-0091, Feb. 1971.

An automatic assembly line was set up for loading and sealing separation charge assemblies. The several operations included cleaning of the cup, filling with propellant, tamping, placing the cover over the cup flange, ultrasonically ring welding the cover to the cup, then blanking the joined cup and cover stock out of the carrier stock. Production rates of 1200 assemblies per hour were achieved, and 50% increase in rate appeared feasible.

332. Joshi, K. C., "The Formation of Ultrasonic Bonds Between Metals." Welding Journal, Vol. 50, Dec. 1971, p. 840-848.

In studies on ultrasonic welding of face-centered cubic metals (aluminum, copper, and gold), bond formation was found to be essentially devoid of interfacial sliding and excess heating and was more than a superimposed stress effect. There appeared to be a unique softening mechanism at the interface, possibly from simultaneous deformation and recrystallization, jog diffusion, and creation of transitory dislocations. Atomic attraction occurred in similar bonds, and mechanical interlocking aided dissimilar bonds. Surface and bulk characteristics were considered important to bondability. Joining parameters must provide the critical amount of energy (power and time) with essentially infinite sliding resistance (optimum clamping force).

333. Jones, J. B., "Ultrasonic Welding for Electrical Conductivity Applications." 83rd Meeting, Acoustical Society of America, Buffalo, N. Y., April 18-21, 1972.

This paper describes ultrasonic welding applications for electrical equipment especially for aircraft, automotive, and applicance industries. Examples described and illustrated included terminal wire connections, armature coils to commutators, field coil assemblies, and consolidation of stranded wire into solid sections. Since the process is effective with both similar and dissimilar metal combinations, it offers versatility in joint design and permits substitution of aluminum wire for copper wire. Its use for economical, fast, automated production was discussed.

334. Thiemann, A. E., "Ultrasonic Tinning of Light Metals." Automobiltechnische Zeitschrift, Vol. 45, 1942, p. 668. (In German)

A new process for soldering or tinning aluminum consists of immersing the aluminum workpiece in a molten solder bath and contacting the sheet with an ultrasonic magnetostrictive transmitter. The vibrations cause the solder particles to hammer against the oxide coating and effect its removal so that the solder adheres firmly to the surface.

335. Alexander, P., "Industrial Applications of Ultrasonics: Researches Carried Out at Siemens-Schuckertwerke, Berlin." BIOS Report No. 1504, British Intelligence Objectives Subcommittee, London, Aug. and Sept. 1946.

Ultrasonic soldering was an application that offered potential since it permitted joining aluminum without flux. Magnetostrictively activated soldering irons and soldering baths for wire tinning were described and illustrated. It was mentioned that Siemens had intended in 1942 to use several hundred of the irons in valve factories, but their manufacture was interrupted by the war.

336. Moss, A. R. and H. R. Brooker, "Some Aspects of German Soldering, Brazing, and Welding Methods." BIOS Report 1844, British Intelligence Objectives Subcommittee, London, Nov. 1946.

Ultrasonic tinning of aluminum wire to replace copper wire in electrical equipment was carried out in Germany. The wire was dipped into a 400°C tinning bath which was vibrated magnetostrictively at 18 kHz. It was found that 1-mm-diameter aluminum wire was completely dissolved by the tinning bath in 20 sec at 500°C or in 60 sec at 300°C. Thus exposure time must be controlled. Aluminum wires were joined by twisting them together and immersing them in the activated bath.

337. Thomas, F. W. and E. Simon, "Soldering Aluminum Alloys." Electronics, Vol. 21, June 1948, p. 90-92. Also K. D. Kahn, "Fluxless Soldering of Aluminum." Welding Engineer, Vol. 33, Aug. 1948, p. 54-58.

Ultrasonic soldering equipment incorporating a magnetostrictive transducer operating at 8 kHz was constructed, and successful results were obtained in tinning 24ST and 75ST aluminum. Stainless steel and chromium-plated surfaces tinned readily when a small amount of cadmium was added to the solder. Phenolic strips were metallized with cadmium, lead, zinc, and aluminum. Anodized and dyed aluminum were tinned with difficulty. No success was achieved with ferrous metals or with magnesium.

338. Dumka, P. S., "Investigation of Ultrasonic Soldering Techniques Applied to Aluminum Alloys." Engineering Note E-1, Instrumentation Lab., Massachusetts Institute of Technology, Oct. 13, 1950; Appendix, Jan. 31, 1952.

A test program was carried out utilizing a British ultrasonic soldering iron and soldering techniques suggested by the manufacturer. Tensile test specimens of bare and Alclad 24S-T joined with 85 Sn-15 Zn solder alloy showed consistently higher joint strength than specimens joined by conventional techniques. Cylindrical specimens ultrasonically soldered with the same solder showed no indications of leaks under vacuum or pressures of 30 psi at room temperature or at 210°F.

339. Nagy, F., "Strength Tests on Aluminum Soldered by the Ultrasonic Method." Aluminium (Budapest), Vol. 2, 1950, p. 238-242, 268-275, 284-293.

The design and construction of an ultrasonic soldering device operating at 14.5 kHz was described. Best bonds in aluminum were obtained with solders of 60 Cd-40 Sn or 60 Cd-40 Zn. Average shear strengths were 5.8-6.4 kg/mm^2, and strength decreased only slightly with 12 hours exposure in sulfuric acid solution. Ultrasonic soldering was considered much superior in every way to conventional soldering techniques.

340. Bradfield, G., "Summarized Proceedings of Symposium on Applications of Ultrasonics." Proc. Physical Society of London, Vol. 63B, 1950, p. 305-322.

The symposium included a discussion of joining fine aluminum wires by ultrasonic soldering. A nickel tube operating at 10 kHz and with a power of 50 watts had a brass cup at its upper end to contain the solder, kept molten by a gas jet. Aluminum and/or copper wires to be joined were twisted lightly and immersed in 70 Sn-30 Zn solder for a few seconds.

341. Noltingk, B. E. and E. A. Neppiras, "Ultrasonic Soldering of Aluminum." Nature (London), Vol. 166, 1950, p. 615.

An aluminum specimen was successfully tinned in a bath of molten solder vibrating magnetostrictively at 18 kHz. The effect could not be reproduced at an ambient pressure of 4 atmospheres; thus the process involved removing the oxide skin by cavitation erosion. Since ultrasonic cavitation is more severe at the lower frequencies, it was expected that ultrasonic tinning would be most effective in this range; this was verified experimentally.

342. Noltingk, B. E. and E. A. Neppiras, "Ultrasonic Soldering Irons." Journal of Scientific Instruments, Vol. 28, Feb. 1951, p. 50-52.

Two ultrasonic devices were developed to facilitate tinning of aluminum: a soldering iron for use with sheet material, and a soldering bath into which wires or other small components could be immersed. Both operated at 22 kHz and with about 50 watts input power. Ultrasonically induced cavitation in the molten solder removed oxide film from the metal surface so alloying could occur. Fluxes were not used, and clean surfaces were not considered essential. A solder alloy of 80 Sn-20 Zn was recommended for corrosion resistance. No success was achieved with chromium, stainless steel, nichrome, or beryllium.

343. Wenk, P. and U. Nündel, "An Ultrasonic Soldering Device for Aluminum." Siemens Zeitschrift, Vol. 25, April 1951, p. 91-94. (In German)

The difficulties with ordinary soldering of aluminum were attributed to the oxide layer on the surface and deficient bonding even with the oxide removed. The effectiveness of ultrasonics in removing the oxide led to the development of an ultrasonic soldering iron incorporating a 20-kHz magnetostrictive transducer. Either the tip and the part to be tinned were immersed in close proximity in a standard tinning bath, or solder was placed on the workpiece and the activated tip stroked over it. After tinning, the parts were joined by ordinary soldering.

344. Crawford, A. E., "The Ultrasonic Soldering of Light Metals." Metallurgia, Vol. 44, Sept. 1951, p. 113-116. Also Crawford, "The Application of Ultrasonic Soldering Techniques." Light Metals, Vol. 15, March 1952, p. 102-104.

The effectiveness of ultrasonic cavitation in removing oxide films from aluminum and its alloys was discussed, and designs were presented for an ultrasonic soldering iron and a soldering bath. A tin/zinc solder was recommended for use with aluminum. Promising applications included electrical connections where aluminum is used to replace copper, hermetic sealing of aluminum cans, repair of defective aluminum castings, and modification of aluminum patterns.

345. Neppiras, E. A., "Ultrasonic Soldering." Metal Industries, Vol. 81, June 1952, p. 103-106.

The article discusses the disadvantages of current standard aluminum soldering techniques, the basic theory of ultrasonic soldering, and the general design principles for ultrasonic soldering equipment. Noted limitations of the process were the very high intensities required for soldering metals such as stainless steel and chromium, the difficulty of satisfactorily

tinning beryllium and titanium, and the susceptibility of all aluminum soldered joints to intercrystalline corrosion.

346. Wenk, P. and H. Boljahn, "Tinning of Aluminum by Means of Ultrasonics." Zeitschrift für Metallkunde, Vol. 43, Sept. 1952, p. 322-324. (In German)

An ultrasonic soldering iron operating at 20 kHz was developed, and its use with auxiliary heating means, such as an electric hot plate or gas flame, was described. Operating time was found to have a significant effect on joint quality and corrosion characteristics. The device was used successfully for tinning aluminum foil, aluminum tubes and bearings, busbars, anodized aluminum parts, window frames, and electrical instruments.

347. "Ultrasonic Soldering in the Foundry." Metallurgia, Vol. 46, Nov. 1952, p. 251-252. Also "Ultrasonic Soldering to Rectify Light-Alloy Castings." Canadian Metals, Vol. 16, Jan. 1953, p. 32-33.

A significant application of ultrasonic soldering was the repair of light alloy castings that ordinarily would be rejected in the foundry. Surface blow-holes and cracks were quickly and permanently filled and an excellent finish obtained. The same techniques were used for repair of aluminum patterns, saving the time and cost of fabricating a new piece.

348. Crawford, A. E., "Ultrasonic Tinning Techniques for Aluminum." Electronics, Vol. 25, Dec. 1952, p. 102-105.

Ultrasonic soldering equipment and techniques were described and a number of possible applications discussed: bonding of radar and television antenna structures, assembly of aluminum chassis, joining of aluminum-foil paper capacitors, hermetic sealing of aluminum cans, repair of light alloy castings, and tinning of aluminum wire to replace copper in transformers and chokes.

349. Walter, L. "Ultrasonic Soldering." Canadian Metals, Vol. 16, Jan. 1953, p. 18, 20.

The principles of ultrasonic soldering and tinning and the cavitation effects in removing oxide films, as well as the principles of equipment design, were discussed.

350. Aeroprojects Inc., "The Corrosion Resistance of Ultrasonically Soldered Aluminum Joints." Research Report 53-79, Oct. 1953.

With a view to evolving techniques for attaching small aluminum ribs to aluminum alloy sheet, joints ultrasonically soldered with tin-base and zinc-base solders were exposed in boiling (95°C) water environment for times up to

1500 hours. The purity of the solder alloy, especially the absence of lead, contributed to corrosion resistance. Tinning time and temperature required careful control, and rib geometry was found to have a significant effect. Application of a sprayed coating of aluminum to the joint provided improved corrosion resistance.

351. Jones, J. B., F. R. Meyer, and C. D. Twardowski, "The Soldering of Aluminum and Its Alloys: A Comprehensive Review of the Literature." Research Report 54-8, Aeroprojects Inc., Army Contract DA-36-034-ORD-1401, March 1954.

This report covers current practices and past research in various methods of soldering aluminum, with emphasis on ultrasonic soldering and its advantages over other methods. The report includes an annotated bibliography on aluminum soldering, with a separate section on ultrasonic soldering.

352. Klosse, E., "The Soldering of Light Metals." Metall, Vol. 8, May 1954, p. 191-192. (In German)

In this review of aluminum soldering techniques, the advantages of ultrasonic soldering for such applications as joining of aluminum cables, repair of damaged castings, and joining of aluminum alloys to copper or brass were delineated.

353. Obrzut, J. J., "Ultrasonics Improve Soldered Joints in Aluminum." Iron Age, Vol. 173, June 24, 1954, p. 97-99.

Ultrasonic soldering equipment was said to produce strong soldered joints in aluminum without the use of flux, even when the metal had been anodized, alodized, or similarly treated. Sound joints were obtained between all types of aluminum sheet, sand castings, die castings, extrusions, tubing, and wire. Aluminum could also be bonded to silver, copper, stainless steel, and magnesium. The process was effective with a wide range of tin-lead and tin-zinc solders.

354. "Three Ways to Use Ultrasonic Soldering on Aluminum Die Castings." Precision Metal Molding, Vol. 7, Nov. 1954, p. 65-66.

Ultrasonic soldering offered new design possibilities for aluminum die castings. Two or more castings could be joined together to obtain complicated shapes difficult to cast. Hermetically sealed assemblies could be produced by this process. Defective castings could be repaired and salvaged. Specially designed soldering tips may be required for certain applications.

355. Jones, J. B. and J. G. Thomas, "Ultrasonic Soldering of Aluminum." AEC Report DP-94, Aeroprojects Inc., Dec. 1954.

Ultrasonically soldered aluminum joints, including nine Sn-Zn-Al and one Zn-Al-Si compositions, in lap and rib-to-plate geometries were exposed to boiling water environment to evaluate possible behavior in heat exchanger applications. Aluminum-spray-protected joints appeared to withstand corrosion for more than 1000 hours; zinc coating was ineffective. It was indicated that heat treatment or stress relief of ultrasonically soldered joints may improve corrosion resistance.

356. Göbel, R., "Critical Considerations on Ultrasonic Tinning of Aluminum." Nachrichtentechnik, Vol. 4, 1954, p. 325-329. (In German)

Experiments to clarify whether ultrasonic soldering is due to diffusion or to bonding were inconclusive and it appeared that both phenomena were involved. Pure tin was considered the most suitable solder for corrosion resistance, but corrosion eventually occurred with exposure to moisture, and lacquer coating was recommended. In strength tests on ultrasonically soldered wire joints, failure always occurred in the wire. Thicker materials also usually failed outside the joint.

357. Lotsmanov, S. N., "Soldering Aluminum and Its Alloys." Gas-Flame Hardening of Metals, Trudy Vsesoyuznoi Nauchno-Tekhnicheskoi Konferentsii, Odessa, 1954, p. 109-118. (In Russian)

Experimentation indicated that ultrasonically soldered joints employing soft solders with low melting points were not dependable, and higher melting alloys were recommended: Al-6 Si-28 Cu, Al-7 Si-21 Cu, and Al-12 Si. Techniques for obtaining sound joints were described.

358. Jones, J. B. and J. G. Thomas, "Ultrasonic Soldering of Aluminum." Research Report 55-24, Aeroprojects Inc., Army Contract DA-36-034-ORD-1401, Feb. 1955.

Ultrasonically soldered aluminum joints prepared with a variety of tin-base and cadmium-base solders were exposed to a boiling water environment, and strength decay as a function of exposure time was evaluated. After 916 hours exposure, the joints had lost 68-94% of their original strength. Solders containing cadmium showed poorest corrosion resistance, while best performance was obtained with 97 Sn-3 Ce, 97 Sn-3 Cu, 100 Sn-trace Ti, and 96 Sn-4 Zn.

359. Potthoff, W. C., "Ultrasonic Fluxless Soldering." Product Engineering, Vol. 26, Oct. 1955, p. G22.

Advantages offered by ultrasonic soldering to the manufacturer included elimination of the use of flux, thus minimizing corrosion and contamination problems, the effectiveness of the process even through oxide coatings, the possibility of using a wide range of standard solder alloys, and the capabilities of soldering parts of various sizes, shapes, thicknesses, and materials. Soldering equipment and procedures were outlined, and several areas of application were mentioned.

360. Carlin, B., "Ultrasonic Soldering Techniques." Electronic Equipment, Dec. 1955.

Ultrasonic soldering irons were designed to satisfy industrial needs without requiring skilled technicians. Magnetostrictive transducers were selected for their ruggedness. Small units contained self-heaters, and larger units were designed for external heating. Both types could be driven by the same 25-watt generator. Solder pots that could be plugged into the same generator were also designed. This equipment was used to solder aluminum busbars and other aluminum parts.

361. Pearce, S. C., "Soft Soldering of Aluminum." Electrical Manufacturer, Vol. 1, Feb. 1956, p. 31-33.

Included was a description of an ultrasonic soldering iron operating at 20 kHz and with a built-on gas torch to supply heat to the workpiece. With this device, aluminum oxide was ruptured, allowing the solder to wet the aluminum. Recommended solders for aluminum were 90 Sn-10 Zn and 80 Sn-20 Zn. To prevent corrosion, the joint should be sealed with lacquer or paint.

362. Hemardinquer, P., "Ultrasonic Applications in Metallurgy and Mechanics." Revue de Générale Mécanique, Vol. 40, Feb. 1956, p. 309-313; Dec. 1956, p. 429-433. (In French)

This survey of ultrasonic applications included an extended discussion of ultrasonic soldering of light alloys, including soldering techniques, soldering irons, types of solders, and various applications. Significant uses were found in tinning of aluminum wire and cable to replace copper, assembly of television antennas and aluminum chassis, joining of aluminum foil condensers, hermetic sealing of aluminum containers, and manufacture of loud speakers.

363. Jones, J. B. and J. G. Thomas, "Strength and Corrosion Resistance of Ultrasonically Soldered Aluminum Joints." Research Report 56-13, Aeroprojects Inc., Army Contract DA-36-034-ORD-1665, March 1956.

Ultrasonic soldering was effectively used to prepare aluminum joints with a variety of tin-base, cadmium-base, and zinc-base solders. Corrosion resistance of the joints to salt solution was compared with earlier results in a boiling water environment. The most effective solder for salt-water immersion was 95 Zn-5 AlSi which was stress-relief-annealed after the joint was prepared. Solders containing zinc alloyed with tin and/or aluminum showed comparatively good resistance. Tin-base solders were more effective for boiling water immersion. It was concluded that solders should be selected specifically for their end-use environments.

364. "Ultrasonic Unit Combines Stripping and Soldering." Electronics, Vol. 29, July 1956, p. 238. Also "Ultrasonic Stripping and Soldering of Leads." Electrical Manufacturing, Vol. 58, July 1956, p. 134-135.

It was determined that enameled wires could be ultrasonically soldered to coil terminals without the use of flux and without prestripping the wire. After wrapping the wire around the terminal, the assembly was dipped in an ultrasonically activated solder pot containing tin-lead solder. The operation was accomplished in less than 2 sec, and the time and uncertainty of hand stripping were eliminated.

365. Jones, J. B. and E. E. Weismantel, "Ultrasonic Joining." Proc. Second RETMA Conf. on Reliable Electrical Connections, Philadelphia, Sept. 11-12, 1956, p. 97-103. Also Jones and Weismantel, "Ultrasonic Metal Joining." Electrical Manufacturing, Vol. 59, April 1957, p. 125-129.

Ultrasonic fluxless soldering and brazing were observed to be applicable to electrical connections, particularly to permit the substitution of aluminum wire for copper wire and to eliminate the use of flux that produces joints of doubtful quality and possibly causes excessive corrosion. Fine wires with insulating coatings were soldered without prestripping. Ultrasonic brazing, an outgrowth of the soldering process, was effective for end uses requiring a higher melting joining alloy (about 850-1250°F), for example, where higher temperatures were required to remove Formvar coatings.

366. Jones, J. B. and J. G. Thomas, "Ultrasonic Soldering of Aluminum." Special Tech. Publication 189, American Society for Testing Materials, 1956, p. 15-29.

Ultrasonic soldering without the use of fluxes eliminates corrosion attack resulting from flux inclusion or inadequate postcleaning. Aluminum joints ultrasonically soldered with several solder alloys were exposed to hot aerated distilled water and salt water, and data were obtained showing

the decay of joint strength with time for each solder in each environment. Corrosion attack caused separation of the joints along the solder-aluminum interface, apparently due to high galvanic potential at the interface resulting from diffusion of solder constituents into the aluminum. Where necessary, selection of a suitable solder permits reasonable life in a corrosive environment.

367. Scarpa, T. J., "Ultrasonic Iron Solders Aluminum." Electronics, Vol. 30, Oct. 1, 1957, p. 168-169.

An ultrasonic soldering iron incorporating a piezoelectric transducer and driven by a Hartley oscillator was described and illustrated. Parts to be soldered were pretinned with this device and then could be joined by conventional methods. The process could be used for tinning aluminum wire for electrical connections, foil for capacitors, and aluminum chassis assemblies.

368. Potthoff, W. C., "The Development of Ultrasonic Soldering." Ultrasonic News, Vol. 1, Oct. 1957, p. 18-19.

Ultrasonic equipment described and illustrated included several sizes of hand-held soldering units, larger units for continuous tinning of aluminum strip at high rates of speed, and a variety of special, interchangeable tips designed for specific production applications.

369. Hanks, G. S., "Soldering of Uranium." Report TID-7562, Minutes of Seventh Annual AEC Welding Conf., Chicago, Nov. 6-8, 1957, p. 191-206. Also Hanks, D. T. Doll, J. M. Taub, and E. L. Brundige, "Soldering of Uranium." TID-8018, Los Alamos Scientific Lab., N. Mex., June 1958.

Joining of uranium was successfully accomplished using several commercial soft solders and fusible alloys. Use of an ultrasonic soldering iron proved the best method for making sound soldered joints of uranium to uranium and to other metals such as stainless steel. Other methods showed some promise but did not give consistently reliable joints. Soldering characteristics of uranium appeared to be similar to those of aluminum.

370. Thomas, J. C. and F. R. Meyer, "Ultrasonic Fusion Joining of Sintered Aluminum Powder Materials to Aluminum Alloys." AEC Report DP-306, Aeroprojects Inc., Feb. 1958.

Essentially void-free fusion-type joints of high strength were produced between Type M-276 sintered aluminum powder plate and 1100-H14 wrought plate, using a technique consisting of brief, controlled exposure of the ends of both

materials to an ultrasonically active coupler face in a bath of molten 1100 aluminum at about 700°C, followed immediately by butt joining and fast cooling. With development, the process should be adaptable to other joint geometries and other SAP types.

371. Grobecker, D. W. and J. B. Duran, "An Evaluation of Ultrasonic Solder Joints." Report SCTM 163-58(16), Sandia Corp., Albuquerque, N. Mex., AEC Contract AT (29-1)-789, April 23, 1958.

A comparison was made of lap joints soldered by ultrasonic methods and by usual flux techniques. Ultrasonic soldering appeared to offer advantages in soldering aluminum with tin-zinc solder and copper with tin-lead solder. Strength of the tin-zinc joints was degraded by exposure in a humid environment, probably because of galvanic corrosion.

372. Tsalyuk, M. and I. Yudenkov, "Ultrasonic Soldering Iron." Radio (USSR), May 1958, p. 54-55. (Army Intelligence Translation H-3741-C)

An ultrasonic soldering iron incorporating a magnetostrictive transducer and driven by an oscillator with automatic frequency control was said to provide a simplification over previous units. Details of the design were presented.

373. Ames, R. S., J. B. Jones, and F. R. Meyer, "Ultrasonic Metal Joining and Machining." SAE Paper 483D, Automotive Engineering Congress, Detroit, Mich., Jan. 8-12, 1962.

Ultrasonic soldering was said to be essentially a modification of conventional soldering, with acoustical vibration as a supplementary energy source. Economical application was generally limited to metallic materials difficult to solder by usual fluxing techniques or to applications in which the use of flux introduced complex processing or end-use problems. The primary advantage was fluxless removal of oxide and other surface films, eliminating the possibility of flux contamination and associated problems. Joints were superior in strength and corrosion resistance, though a protective coating was recommended for corrosive environments. Current and potential applications were discussed.

374. Shuster, K. Sh. and A. G. El'kin, "UVL-4 Ultrasonic Tinning Bath Used for Electric Motor Wiring." Byulleten' Tekhnicheskoy Informatsii No. 12, Moscow, 1963, p. 64-65. (U. S. Dept. of Commerce Translation TT 64-21697)

A new ultrasonic bath for fluxless tinning and soldering of aluminum and copper wires comprised the introduction of vibration through a wave guide

concentrator connected to the bath, rather than through the bottom or walls of the bath as in previous devices. Thus only the molten solder was subjected to vibration. The time required for soldering lead wires for electric motors was reduced 2.5 times in comparison with previous ultrasonic baths.

375. Alexander, N. W., "Ultrasonic Tinning and Soldering." Electrical/Electronic Production, May-June 1964, p. 4-5.

It was observed that ultrasonic soldering has not gained greater acceptance in production lines because of serious equipment limitations, lack of techniques and tooling, and lack of effort to automate the process. It has, however, been effectively used in non-electronic applications to make hermetic seals, assemble small bellows, and seal cans and tubulations, and increasing uses were forecast. Any specific manufacturing process should be planned carefully to take full advantage of this process.

376. "Ultrasonics Permits Brazing Complex Stainless Steel Assembly Without Flux." AEC-NASA Technical Brief 67-10094, April 1967.

Ultrasonic brazing was used to seal 0.090-in.-diameter instrumentation tubes into a seal plug, for which a fluxless operation was required. Ultrasonics insured that the brazing material would flow down the tube lengths to provide the seal. Oxidation of the plug surface (before the holes for the tubes were bored) prevented brazing material from flowing onto the plug face rather than into the holes. The completed assembly withstood a pressure of 600 psi of hydrogen.

377. Le Grand, R., "Ultrasonics Gets 3 New Jobs." American Machinist, Vol. 115, Feb. 8, 1971, p. 58-64.

The techniques and advantages of ultrasonic soldering were discussed. Typical applications in pilot or full production included pretinning of aluminum wire ends or aluminum tubing, sealing steel containers, sealing pressure vessels without flux, and numerous electronic applications. The process permitted the use of aluminum wire to replace copper wire.

378. Fuchs, F. J., "Solve Soldering Problems with Ultrasonics." Assembly Engineering, Vol. 15, July 1972, p. 58-60.

Recent advances in ultrasonic soldering equipment were said to solve such problems as insufficient volume or non-uniformity of the cavitation field, incompatibility with corrosive and high-temperature alloys, and rapid erosion and deterioration of transducers. Precleaning to remove contaminants was recommended to avoid residue accumulation in the solder bath and secure a strong joint. The importance of preheating large parts was emphasized. The parts were either ultrasonically tinned and joined with heat application or

were immersed in a solder pot. Tinning time and temperature must be carefully controlled. Solders of 100 Zn and 95 Zn-5 Al were recommended for aluminum for wetting ability and corrosion resistance.

379. Konovalov, E. G., V. K. Stanishevskii, and Zh. S. Vorob'eva, "Study of the Capillary Effect of Solder Melts Under the Action of Ultrasound." Doklady Akademii Nauk BSSR, Vol. 16, No. 6, 1972, p. 516-517. (Translation: Russian Ultrasonics, Vol. 2, July 1972, p. 149-151)

The effectiveness of ultrasonic soldering in penetrating crevices was evaluated using a 20-kHz ultrasonic tinning bath with a 300-mm capillary set up in the center. Without ultrasonics, the solder rose in the capillary to about the level of the bath. When ultrasonics was switched on, the capillary continued to rise for about 14-20 sec, and with ultrasonic intensity of 16 w/cm^2 showed a height rise of 118 mm. Thus ultrasonics should accelerate the soldering of porous materials and unusual geometries.

Diffusion Bonding

380. Polyakov, L. M., G. N. Malik, and R. I. Garber, "The Sintering of Copper by Ultrasonic Irradiation." Physics of Metals and Metallography (USSR), Vol. 10, No. 4, 1960, p. 97-103.

Vacuum sinter-joining of copper washers, carried out under 19-kHz ultrasonic influence at temperatures up to 1000°C and with axial loads up to 300 kg, permitted substantial reduction in sintering times; for example, from 1 hr to 30 sec at 875°C, from 3 hr to 3 min at 700°C, and from 8 hr to 6 min at 600°C. Little plastic deformation occurred, and the treated material showed extensive recrystallization grain refinement.

381. Thomas, J. G., "Ultrasonically Accelerated Diffusion Bonding of Beryllium." Research Report 71-22, Aeroprojects Inc., Navy Contract N00156-70-C-1613, July 1971.

Diffusion bonding of beryllium was carried out with a 15-kHz torsional welding system installed in a vacuum chamber with an induction heating system. Effective non-ultrasonic diffusion bonds were obtained at 770°C and 1500 psi for 3 hr and at 825°C and 4500 psi for 2 hr. Equivalent bond quality was obtained at 675°C and 4500 psi for 15 min with a 25-sec pulse of 300-watt ultrasonic energy at the beginning of the bonding cycle. This represents a temperature reduction of 12-18% and a reduction in time of 87-92%.

382. Maropis, N., J. G. Thomas, and F. R. Meyer, "Ultrasonic Tool for Providing Leaktightness on Flared Tubing Connections." Research Report 65-105, Technidyne Inc., NASA Contract NAS 8-11965, Nov. 1965. Also H. T. Blaise and Maropis, "Development of Ultrasonic Wrench for Flared Tubing Connections." NASA TM X-53550, Marshall Space Flight Center, Huntsville, Ala., Dec. 8, 1966.

An ultrasonic torque wrench for tightening flared tubing connections of 1/4-inch aluminum and 1/2-inch stainless steel was designed, built, and evaluated, after preliminary investigation of vibratory modes, frequencies, power levels, and pulse times. The wrench head vibrated in the flexural mode at 28 kHz and was rated at 300 electrical watts input power on a continuous duty basis. Ultrasonic activation permitted additional rotation of the fittings and yielded a high percentage of leaktight assemblies; increased breakaway torque was required for disassembly of the ultrasonically tightened connections.

383. Dyke, R. A., "Metallographic Examination of Flared Tubing Connections." Report TIR-MW-59-66, Marshall Space Flight Center, Manufacturing Engineering Lab., Huntsville, Ala., Aug. 10, 1966.

Metallographic examination of nine ultrasonically torqued flared tubing connections was conducted to determine mechanical reasons for sound and leaker assemblies. Four assemblies with commercial fittings did not leak, and three of five connections assembled with MC fittings leaked. Microhardness determinations revealed that the commercial fittings were softer than the flared tubing, while the MC fittings were harder than the tubing. In all cases, the sleeve was harder than the tube. Leakage occurred when the fitting was harder than the tubing; no leakage with the reverse.

384. Maropis, N. and F. R. Meyer, "Ultrasonic Wrench for Flared Tubing Connections." Report CR-89965, Technidyne Inc., NASA Contract NAS 8-11965, Sept. 1967. Also E. J. Minter, "Ultrasonic Torque Wrench." NASA TM X-53995, Marshall Space Flight Center, Huntsville, Ala., March 20, 1970.

Manual and semi-automatic wrenches for tightening flared tubing connections with interchangeable heads for tubing sizes ranging from 1/8 to 1 inch diameter were designed and fabricated. Ultrasonic activation of the wrench head increased the percentage of leaktight assemblies with 6061-T3 aluminum alloy components by 73% and of 304 stainless steel components by 26% without increasing applied torque. Ultrasonic torquing increased rotation of the nut by an average of 14^{o}, increased measured tensile strains in the nut, produced higher sealing stresses on the tube flares, and required increased breakaway torque to loosen the assemblies. The effect was attributed to reduced friction between the mating threads.

Wrenching

385. "Ultrasonic Wrench Produces Leaktight Connections." NASA Technical Brief 67-10353, Oct. 1967.

An ultrasonic wrench was designed to insure greater reliability in obtaining leaktight assemblies in flared tubing connections by reducing frictional forces between contacting members. The wrench system induced a flexural vibratory node in the nut and incorporated a lead zirconate titanate transducer. Acoustically designed, 12-point, open-end wrench heads for several size fittings were mechanically interchangeable. The complete wrench assembly weighed approximately 11 pounds.

386. Kartluke, H. and H. D. Edelson, "Ultrasonic Tightening of Threaded Fasteners." Research Report 68-48, Aeroprojects Inc., July 1968.

In the installation of 1-in. bolts in steel plate, 15-kHz torsional activation of the nut effected 25-30% increase in bolt tension and 10% increase in reaction at the bolt head at a given torque level. The effect increased with increasing power. Measured residual torsional stress in the bolts was less than with non-ultrasonically torqued nuts. The process had no effect on tension in previously tightened bolts in the same assembly, and no apparent effect on deformation of nut and bolt threads. Ultrasonic axial excitation of the bolt during torquing also showed a significant effect and should be investigated further.

387. Maropis, N., D. Elmore, and F. R. Meyer, "Ultrasonic Wrenching of Gear Shaft Assemblies." Research Report 68-54, Aeroprojects Inc., Aug. 1968.

An experimental 15-kHz ultrasonic torsional system was used to tighten gear shaft assemblies; the procedure involved installation of a plane nut in one end of the assembly and a retainer in the opposite end. Tension developed in the gear shaft averaged 23% higher than for non-ultrasonically tightened assemblies at the same torque level. Breakaway torque required to loosen the assemblies ranged from 22 to 40% higher for the ultrasonically tightened assemblies. A design concept was evolved for an ultrasonic torque stand for production evaluation in this application.

388. Jones, G. H. and E. A. Quinn, "Semi-Automatic Ultrasonic Wrench Evaluation." MEL Tech. Report ND-230-68, Hayes International Corp., MEL Operation, Sept. 13, 1968.

The semi-automatic ultrasonic wrench for flared tubing connections was independently evaluated in tightening six sizes of aluminum and steel tubing connections. Ultrasonic activation increased relative rotation between nut and union by 2%, increased the tension load at the same torque level by 8.8%, increased the average sealing pressure by 2185 psi, and increased the required breakaway torque in amounts from 2 to 27%. Repeatability of the wrench was considered good but accuracy was poor. Its use in confined areas was restricted because of the large wrench heads and long handle.

Wrenching

389. Kartluke, H., N. Maropis, and F. R. Meyer, "Feasibility Study of Ultrasonic Wrenching of Bolt-Nut Assemblies." Research Report 69-35, Aeroprojects Inc., Oct. 1969.

Torquing of 7/16-in. hex-head Lamalloy bolts and nuts was accomplished with 15-kHz ultrasonic activation of the nuts in vibratory modes transverse, axial, torsional, or combined axial-torsional with respect to the bolt axis. The torsional mode was most effective. At a given torque level, bolt tension was increased by up to 35%, scatter in tension values was reduced to about half the non-ultrasonic value, and breakaway torque was substantially higher. Requirements for a production prototype ultrasonic torquing system were delineated; 600 electrical watts input to ceramic transducers was considered adequate.

Press Fitting

390. Jones, J. B., N. Maropis, and J. G. Thomas, "Specialized Applications of Ultrasonic Energy." Research Report 57-10, Aeroprojects Inc., Dec. 1957.

Experiments with assembly and disassembly of a close-fitting ring and mandrel indicated that ultrasonic vibration normal to surfaces in contact with each other reduced friction. Several long aluminum tubes, warped in extrusion and believed incapable of being telescoped upon each other by ordinary methods, were successfully coaxially assembled when excited by vibratory energy.

391. Fridman, H. D. and P. Levesque, "Reduction of Static Friction by Sonic Vibrations." Journal of Applied Physics, Vol. 30, Oct. 1959, p. 1572-1575.

The effect of vibration on the static coefficient of friction was investigated in experiments with a steel block sliding on an inclined plane of highly polished steel. A nickel transducer, threaded and bolted into the steel plate, vibrated the plate at frequencies within the range of 6-42 kHz. Even at low amplitudes, the static friction was reduced to essentially zero. With sufficient vibratory power, the highly polished steel block could be made to ride uphill at a slight incline, thus yielding effectively a negative value of the static friction coefficient.

392. Aeroprojects Inc., "Ultrasonic Press Fitting of Metal Components." 1963.

The ultrasonic effect in reducing friction between contacting metal surfaces was demonstrated with the fitting of a step-tapered square aluminum mandrel within a 2-in.-ID aluminum tube. With 20-kHz ultrasonic flexural

activation of the tube at a transducer input power of 100 watts, an interference fit of 0.002 in. was obtained. Without ultrasonics, a zero-clearance fit could not be obtained. Vibration had the further effects of reducing force requirements and minimizing scoring of the mating surfaces.

393. Balamuth, L., "Recent Developments in Ultrasonic Metalworking Processes." SAE Paper 849G, Air Transport and Space Meeting, New York, April 27-30, 1964. Also Balamuth, "Ultrasonic Metalworking." American Machinist, Vol. 108, April 13, 1964, p. 136-138.

Ultrasonic vibration was used to facilitate pressed and forced fits. A hardened steel rod was forced into a hardened steel hole with an interference of at least 0.0001 in., using radial vibration of the drilled block and axial vibration of the rod. Metal inserts were readily sunk into plastic bodies by the hammering effect of vibration.

394. Balamuth, L., "Ultrasonics as Applied to Metal Forming and Assembly Processes." SAE Paper 650762, National Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, Oct. 4-8, 1965.

Vibration fitting, where classes of fits are important, was observed to be a recent metal-to-metal assembly technique. It was possible to produce an interference fit of hardened parts at considerably reduced static forces. A theory stated that local thermal equivalence effects combined with periodic local changes in dimensions and friction reduction were responsible for the lowered force requirement.

395. Bayles, W. H., "The Application of Ultrasonic Energy to the Insertion of Hi-Lok-Type Fasteners." Research Report 69-41, Aeroprojects Inc., Nov. 1969.

The use of a pneumatic hammer for interference-fit of Hi-Lok type fasteners in sheet or plate material was ordinarily accompanied by galling or seizing due to high frictional forces, and complete seating was frequently not obtained. From limited experimentation with equipment designed for other purposes, ultrasonics applied in conjunction with static force appeared to improve seating of 1/4-in. titanium alloy fasteners into titanium alloy plate with 0.004-in. interference, and to reduce the required static force.

396. Behr, A., "A Possible Application of Ultrasonics." Metal Industry (London), Vol. 63, Dec. 31, 1943, p. 422.

On the basis of demonstrated ultrasonic effects on molten metals, ultrasonic application to spot welding was considered promising because of the small volume of metal exposed. It was postulated that cast nugget structure could be broken up and mechanical properties increased. Ultrasonics could be introduced through one electrode or through an auxiliary electrode contacting the metal, and could be timed to coincide with certain stages of weld formation.

397. Willrich, H. O., R. L. H. Butterfield, A. J. Hipperson, G. L. Hopkins. and A. R. Moss, "Welding Research and Development in Germany." BIOS Report 1849, British Intelligence Objectives Subcommittee, Jan. 1946.

A German development during World War II involved research into the ultrasonic effect on resistance spot welds in aluminum alloy sheet. Grain size and cast structure were reduced, change from parent metal to weld nugget was more gradual, and strength was increased by about 35%. No frequency effect was noted in the range between 2 and 20 kHz. Difficulty was noted with detuning of the system during welding, and parallel tests with low frequencies produced better results.

398. Siemens-Schuckertwerke A.G., "Experiments on Spot Welding of Duraluminum Sheets with the Application of Sonic or Ultrasonic Vibrations." BIOS Trip 1697, British Intelligence Objectives Subcommittee, London, Feb. 4, 1946. Also W. H. Willrich, "Applications of Ultrasonic Waves." Welding (London), Vol. 18, Feb. 1950, p. 61-66.

Consideration was given to ultrasonic application during arc welding, and an arrangement was devised in which vibratory energy from a quartz crystal was transmitted through an oil bath to the electrode. The arrangement was considered promising, but vibratory losses due to reflection and absorption prevented effective operation.

Investigations were also carried out to determine equipment arrangements and welding conditions whereby ultrasonic application could improve the structure of resistance spot welds. Considerable difficulty was encountered with detuning and damping of vibratory amplitude with application of welding pressure. Best results were obtained when the magnetostrictive vibrator was inclined at 45° to the welding electrode axis. Powers up to 1000 watts were used, and no frequency effect was found between 4 and 20 kHz; the effect increased with increasing weld time. The grain structure was substantially refined, and in thin sheets the fusion zone was entirely absent.

399. Alexander, P., "Industrial Applications of Ultrasonics: Researches Carried out at Siemens-Schuckertwerke, Berlin." BIOS Report 1504, British Intelligence Objectives Sub-Committee, Sept. 1946.

Ultrasonics applied to electrical welding proved of doubtful value. Sheets to be joined were clamped between welding electrodes of magnetostrictive material, and electrodes were set into vibration as current was applied. Improvement in crystal structure and decrease in grain size were obtained, but no appreciable increase in strength.

400. Jones, J. B., F. J. Turbett, and J. V. Kane, "Exploratory Research on the Application of Ultrasonics to Spot Welding." Research Report 50-5, Aeroprojects Inc., Navy Contract NOa(s)-10459, Aug. 1950.

The effects of ultrasonics on spot welds in aluminum alloy were investigated at frequencies of 15, 300, and 1000 kHz; positive results were obtained only at 15 kHz. Improvements were noted in shear strengths, in coefficients of variation, and in the incidence of cracks. In some instances, the microstructure of the ultrasonically treated welds showed grain refinement, more random orientation of the cast structure, and blending of the cast metal into the wrought grains of the rolled sheet.

401. Welty, J. W., "Effect of Vibration on Weld Metal." Welding Journal, Vol. 31, Aug. 1952, p. 361s-366s.

Resistance welding experiments were carried out with 8.6-kHz vibration introduced through magnetostrictive electrodes, using 9900 amp, 0.2 sec weld time, and 1000 psi pressure. No significant difference was found in nugget pattern or metal structure, but the vibrated specimens showed slightly higher torsion-shear strength. Although data were somewhat inconsistent, the general trend slightly favored the vibrated specimens.

Inert-gas-shielded arc welding of 347 steel was carried out under the influence of vibration over a range of frequencies. Although results were variable, the vibrated specimens generally showed more random grain orientation with less dendritic growth. At frequencies below 15 kHz, there was an apparent loss of ductility. Maximum improvement was obtained at 28-30 kHz.

402. Jones, J. B., C. DePrisco, and F. R. Meyer, "Investigations of Ultrasonics Applied to Spot Welding." Research Report 53-18, Aeroprojects Inc., Navy Contract NOas 51-612-c, June 1953.

Efficient ultrasonic 15-kHz transducer-couplings were developed for application to spot welding of 0.051-in. aluminum alloy sheet during various stages of the process. Variability in shear strengths was reduced, although there

was no significant change in weld microstructure. Best welds were obtained with ultrasonic application at medium power levels during the forge portion of the weld cycle. In a supplementary study, ultrasonic application through the spot welder electrodes effectively reduced the electrical resistance of as-received aluminum sheet generally to within specification limits. Occasionally the sheets adhered together with ultrasonics but without welding current (this observation eventually led to the development of ultrasonic welding).

403. Arbuzov, Yu. P., "The Application of Ultrasonic Vibrations During the Argon Arc Welding of Aluminum Alloys." Aviatsionniyi Promyshlennoe Stroitel'stvo, 1957, No. 9, p. 29-31. (In Russian)

Ultrasonic application at 18 kHz and 0.5 kw power during argon arc welding with a consumable electrode had no apparent effect on the structure or strength of the specimens. It was believed that insufficient vibratory power was used.

404. Erokhin, A. A., Y. I. Kitaigorodskii, M. G. Kogan, and L. L. Silin, "Effect of Vibrations of Ultrasonic Frequency on Crystallization Pattern of Weld Puddles." Izvestiya Akademii Nauk SSSR, Otdelenie Tekhnicheskikh Nauk, 1958, No. 1, p. 140-142. (Brutcher Translation 4905)

Ultrasonic vibration at 19.5 kHz and 2.0-2.5 kw power was applied during submerged arc and argon arc welding of austenitic stainless steel. When the workpiece was vibrated, a finer weld structure was obtained, but a cracking tendency was noted. Grain structure was finer when the weld metal itself was vibrated, although there was still dendritic structure in the lower zones of the weld.

405. Russo, V. L., "Effect of Ultrasonic Vibrations on the Crystallization of Weld Puddles and on the Properties of the Metal in the Joint." Svarka, Sbornik Statei, 1959, No. 2, p. 3-8. (In Russian)

A rod vibrating at 29 or 80 kHz was immersed in the molten puddle during argon arc welding of aluminum alloy. This refined the grain structure of the weld metal and increased its elongation by 25%. The lower frequency also slightly increased yield and tensile strength. Effectiveness of the treatment increased with increasing vibratory power but varied little with frequency.

406. Erokhin, A. A., G. F. Balandin and V. D. Kodolov, "Effect of Ultrasonic Vibrations on Weld Crystallization in Electroslag Welding." Automatic Welding (USSR), 1960, No. 1, p. 18-24.

Ultrasonic vibration during electroslag welding of austenitic stainless steels resulted in a fine-grained weld structure accompanied by 15-20% increase in impact strength. The columnar structure was rearranged, and there was more even distribution of nonmetallic inclusions in the whole metal volume. The welds appeared to be less susceptible to hot cracks than conventionally made welds.

407. Lebiga, V. A., "Effect of Ultrasonic Vibrations on Crystallization of Welds in Automatic Welding." Automatic Welding (USSR), 1960, No. 1, p. 21-26. (In Russian)

Ultrasonic vibration at 10-50 kHz during welding of bronze and several types of steel effectively broke up the columnar structure of the weld metal and produced equiaxed grain structure with uniform distribution of impurities. The vibrations were most effectively introduced into the molten pool. The power required was 1000 watts for submerged-arc welding and 2000-3000 watts for electroslag welding.

408. Silin, L. L., "The Influence of an Ultrasonic Field on the Structure and Formation of Cracks in the Metal of a Joint During Arc Welding." Izvestiya Akademii Nauk SSSR, Otdelenie Tekhnicheskikh Nauk, Metallurgiya i Toplivo, 1960, No. 3, p. 39-43. (Brutcher Translation 4906)

In the arc welding of heat-resistant alloys under 20-kHz ultrasonic influence, the degree of grain refinement depended on vibratory amplitude. Above a certain level, weld appearance deteriorated, excessive spatter occurred, and nonmetallic inclusions formed in the beads. Cracks formed when the alternating elastic deformations exceeded the ductility of the metal. Extent of cracking depended on metal composition. Increased grain refinement was accompanied by reduced proneness to cracking.

409. Silverstein, S. M., J. N. Antonevich, R. P. Sopher, and P. J. Rieppel, "Welding Tantalum for High-Temperature Systems." Metal Progress, Vol. 77, June 1960, p. 103-109.

In the arc welding of tantalum, ultrasonic vibration was found to decrease grain size of the solidified weld metal to about one-third that of unvibrated specimens. Coupling difficulties limited the work to simple bead-on-plate welds. Metallographic studies showed that etching attack on grain boundaries was greater for vibrated than unvibrated specimens, and this may limit corrosion resistance of such joints.

410. D'Antonio, C. and A. J. Vecchio, "Effect of Ultrasonic Agitation on Grain Size in Welds." Welding Journal, Vol. 41, April 1962, p. 166s.

A tungsten-arc inert-gas weld in titanium alloy showed significant grain refinement when the weld pool was ultrasonically agitated during welding.

411. "Pulsonic Welding: The Development of a New Joining Technique." Welding and Metal Fabrication, Vol. 30, June 1962, p. 235-239.

Pulsonic welding was said to combine ultrasonic welding with a resistance heating source, with the vibration applied axially through the electrode and with light pressure to avoid damping. The equipment could be used for welding by resistance heating alone, by ultrasonics alone, or with combined operation. The process produced grain refinement, small heat-affected zones, altered metallurgical structure, ductility, and low deformation, and could be effectively used with a variety of similar and dissimilar metals.

412. Balandin, G. F. and V. D. Kodolov, "The Use of Ultrasonics in Automatic Electroslag Welding." Automation of Mechanical Engineering Processes, Vol. 2, Akademii Nauk SSSR, 1962, p. 209-213. (In Russian)

The process of crystallization of the metal of an electroslag weld was favorably influenced by ultrasonic application. Ultrasonic waves were introduced into the weld pool by a wire passing through a special waveguide slide arrangement. Grain size of the weld metal was significantly decreased, columnar structure was disrupted, and there were fewer imperfections due to hot cracks.

413. Ol'shanskii, N. A. and A. V. Mordvintseva, "Ultrasonics in Welding." Ultrasound in Industrial Processing and Control, Soviet Progress in Applied Ultrasonics, Vol. 1, Mashgiz, Moscow, 1959, p. 58-68. (Translation: Consultants Bureau, New York, 1964)

Ultrasonic application to fusion welding may be accomplished in several ways: by transmitting the vibrations through an air gap, by immersing the end of the waveguide in the molten metal, by transmission through the sheet material, or by superimposition directly on the arc. The effects included reduced porosity in the weld metal, breaking up of grain structure, and increasing hardness. Ultrasonic peening of a weld seam after welding substantially reduced deflection of plate material as well as residual stresses and strains. The weld metal showed increased hardness and ductility.

414. Sonea, I., "Effect of Ultrasound on Crystallization Processes in Welds Produced by an Automatic Submerged-Arc Process." Conf. for Welding Technique and Metal Testing, Vol. 1, Timisoara, Rumania, Sept. 28-Oct. 2, 1965, p. 639-645. (In German)

Welding units using ultrasonic vibrations to improve the crystalline structure of welds were described. The theoretical and practical aspects of the techniques were considered in terms of the quality of the welds. Photomicrographs were provided to illustrate the results.

415. Gellert, R., "Vibrations--New Aid to Joining." SAE Paper 650761, National Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, Oct. 4-8, 1965.

A project in ultrasonic fusion welding was undertaken to improve surface wetting, reduce fusion temperatures, improve grain structure in the weld zone, reduce alloy component separation, and reduce residual stresses at the joint. Initial results showed a 50% decrease in grain size, greatly improved surface wetting, and a decrease in fusion temperature with less than 50 watts of ultrasonic power.

416. Kevern, J., "Ultrasonics: Intense Energy With a Delicate Touch." Product Engineering, Vol. 39, April 22, 1968, p. 102-110.

Investigations were conducted in tungsten inert-gas welding with 20-kHz vibration applied to the top side of the workpiece ahead of the weld deposit and with controlled pressures of 0-80 psi. A weld in 2014 aluminum showed marked refinement of the as-cast structure in the lower half of the melt. Dendrites were still present in the upper half of the nugget but were broken up into finer crystals.

417. Matveev, J. M., "Ultrasonic Application During Welding of Tubes of Ch18N10T Steel Tubes." Welding Production (USSR), 1968, No. 4, p. 58-61.

In the gas-shielded arc welding of 38-mm diameter steel tubes, ultrasonics at a frequency of 18-19 kHz and power of 3-4 kw was applied through the workpiece using a pin-type tip. When the pin was suitably located, dendritic formation was almost completely absent. If the power level was too high, cracks formed and propagated. The ultrasonically treated weld beads were less susceptible to intergranular corrosion. It was noted that weld structure improved as the tube wall thickness was increased.

III. PATENT LITERATURE

Patents issued on the various ultrasonic metalworking processes are presented in generally the same categories and individual processes as the general literature. As in the preceding section, both ultrasonic and foreign entries are included.

Frequently a patent on a process is filed in more than one country. Such patents are cited only once, and generally under the country of original filing. Where the original specification was not available, as in the case of several foreign patents, notation is made of the country and date of original filing.

The patents are arranged under each subject according to the date of the patent grant, if this date is noted on the document. Where the document includes only the filing date (as in the case of some of the Russian patents), this date governs the order of inclusion.

The patents are numbered consecutively with a "P" prefix to distinguish them from the general literature of the previous section.

D. METAL JOINING

A. GENERAL

P1. Elmore, W. C. (Aeroprojects Inc.), "Support for Vibratory Devices." U.S. Patents 2,891,178, 2,891,179, and 2,891,180, June 16, 1959 (filed Aug. 19, 1957).

These patents relate to variations of force-insensitive resonant support mounts for use with vibratory devices, including soldering, drilling, welding, and machining equipment and the like, to enable effective support of such vibratory devices while minimizing frequency shift and energy loss to associated members, even when the device is applied to a work area with force and under load. A basic embodiment consists of a cylindrical metal sleeve 1/2-wavelength long with one end attached to the vibratory device and the rest of the cylinder free from attachment, and with a flange midway between the free and joined ends for attachment to a supporting surface, thus permitting support at a true node location.

P2. McGunigle, R. D. (Gulton Industries, Inc.), "Piezoelectric Ultrasonic Transducer." U.S. Patent 2,947,886, Aug. 2, 1960 (filed April 29, 1958).

An ultrasonic device as for a drill or welder incorporates a mechanical transformer substantially conical in shape and consisting of three tapered sections of differing slopes, with the transitions at velocity nodes. Several transducers may be attached to the larger end of the transformer, and a rigid plate grooved to accommodate the transducers is used to clamp the transducers at their upper ends. A resilient material is placed within the grooves in contact with the transducers, and compression is applied through bolts between the rigid plate and a mounting flange on the transformer.

P3. Jones, J. B. (Aeroprojects Inc.), "Ultrasonic Devices." U.S. Patent 3,038,358, June 12, 1962 (filed Dec. 30, 1957).

An ultrasonic device for use at high power levels, as for welding, soldering, brazing, and machining, is provided with a mechanically replaceable tip whose surfaces are machined to closely mate with those in a recess in the tool holder, the tip being held in place by a threaded collet. Such a tip used on a metal welder is positively driven without play, minimizes the possibility of fatigue failure and energy loss at the interface between tip and coupler, and provides an efficient ultrasonic device at low cost.

P4. Mason, W. P. (Bell Telephone Labs., Inc.), "Methods and Apparatus Employing Torsionally Vibratory Energy." U.S. Patent 3,131,515, May 5, 1964 (filed Jan. 4, 1960).

The operation and effectiveness of ultrasonic tools such as drills and welders can be improved by substituting a torsionally vibrating horn for the longitudinally driven horns of prior arrangements, in order to subject the workpiece to maximum particle velocities and greater concentration of vibratory energy at the small end of the horn.

GENERAL

P5. Jones, J. B., C. F. DePrisco, and N. Maropis (Aeroprojects Inc.), "Vibratory Device for Delivering Vibratory Energy at High Power." U.S. Patent 3,148,293, Sept. 8, 1964 (filed June 5, 1961).

Substantially increased ultrasonic power delivery can be achieved through a single acoustical conductor having a cross section of fixed dimensions when one end of this member terminates in at least two separate arms with the included angle between them being less than about 76°. Separate transducers attached to each arm operating at essentially the same frequency and in the same phase transmit higher vibratory power levels than can be achieved with a single transducer. The device is effectively used with ultrasonic welding and extrusion equipment and for other high-power applications.

P6. Balamuth, L. (Cavitron Ultrasonics Inc.), "Energy Storage in High Frequency Vibratory Devices." U.S. Patent 3,341,935, Sept. 19, 1967 (filed April 23, 1964).

Means are provided for reducing power requirements for vibrating a work tool in performing operations such as machining, forging, dimpling, forming, welding, etc., particularly when the vibratory energy is to be intermittently applied to the workpiece, by storing energy within the work tool and connecting body, in a manner analogous to a flywheel connected to an electric motor. Thus ultrasonic motors and generators of reduced power output can be used. The transmission means is provided with an energy storage capacity at least 20 times as large as the quantity of energy received by the work during a work period.

P7. Balamuth, L. (Cavitron Corp.), "Ultrasonic Motor System." U.S. Patent 3,396,892, Aug. 13, 1968 (filed Jan. 20, 1966).

An ultrasonic system for performing work, such as forging, dimpling, drawing, extruding, swaging, and welding, is directed to employing vibratory energy at a displacement nodal region of vibratory motion in order to avoid damping out of the vibration when pressure is applied. Embodiments for the various applications are described and illustrated.

P8. McMaster, R. C., C. C. Libby, and H. M. Minchenko (Ohio State University), "Sonic Transducer Apparatus." U.S. Patent 3,475,628, Oct. 28, 1969 (filed Dec. 28, 1966).

A high-power, high-Q electromechanical transducer is coupled to a tool in a work environment so that the tool does not form part of the transducer resonant structure, thus permitting the transducer to develop full power capability; in an alternate arrangement, means are provided for coupling the transducer to work surfaces having various configurations without loss of motion of the tool after impact with the work to be absorbed by the transducer. Various types of tools are illustrated.

P9. McMaster, R. C., C. C. Libby, and H. M. Minchenko (Ohio State University). "Sonic Transducer Apparatus." U.S. Patent 3,558,937, Jan. 26, 1971 (filed March 13, 1969).

The invention provides means for coupling a high-power, high-Q electromechanical transducer to drive a tool effectively for workpieces having various configurations, without loss of power capability. The tip of an elongated transmission element is maintained in an out-of-line relationship with the longitudinal axis of the workpiece, and the resonant frequency of the transducer is out of phase with the resonant frequency of the workpiece. This arrangement, used for riveting, drilling, and other operations, permits delivery of high amounts of energy into relatively thin workpieces.

B. METAL FORMING

General

P10. Lintner, K., D. Oelschlagel, E. Schmid, and B. Weiss, "Process for Facilitating the Chipless Deformation of Metallic Workpieces." Austrian Patent 240,136, Sept. 15, 1964 (filed Nov. 8, 1963).

Annealing of metallic materials between forming steps is carried out under influence of ultrasonic vibrations, either by direct coupling into the workpiece or through an oil bath, in order to shorten annealing time and/or reduce annealing temperature.

P11. Butler, R. D., I. F. Bowers, and C. C. E. Colley (Pressed Steel Fisher Ltd.), "Method of Forming Sheet or Plate Material." U.S. Patent 3,529,457, Sept. 22, 1970 (filed Dec. 15, 1967; priority in Great Britain Dec. 23, 1966).

This invention concerns a method for forming sheet or plate material that exhibits superplasticity within a limited temperature range. One face of the material is exposed to a liquid (such as molten metal or suitable oils or salts) heated to within or above this temperature range, and sufficient pressure is applied to the liquid to force the sheet toward a die at a strain rate below the critical value. High-frequency vibration (above 10 kHz) is applied to the heated liquid, in order to improve formability of the metal.

P12. Turk, C. D. and J. F. Clarke (Texas Instruments Inc.), "Products Composed of Superplastic Crystalline Materials." U.S. Patent 3,536,539, Oct. 27, 1970 (filed Jan. 11, 1968).

Metals and other materials capable of superplasticity are subjected to energy input by ultrasonic application in order to achieve conventional drawing, pressing, and the like under acceptably low temperatures without incurring deleterious localized stresses. The process is illustrated with reference to a zinc-aluminum crystalline material.

P13. Minchenko, H. M. and L. A. Kendall (Ohio State University), "Sonic System for Deformation of Sheet Material." U.S. Patent 3,643,483, Feb. 22, 1972 (filed Aug. 13, 1969).

A system and process are described for cold bending and drawing of metals under vibratory influence, consisting of an ultrasonically excited forming punch and a mating die positioned opposite the punch with the metallic material inserted between. The intermittent impacts made by the punch against the metal blank effect forming in one continuous operation with much lower static loading than is conventionally required. This provides a method for working materials not normally considered cold-formable.

P14. Rosenthal, A. H. (Scophony Corp. of America), "Apparatus for Drawing Wire." U.S. Patent 2,568,303, Sept. 18, 1951 (filed Oct. 4, 1944).

Wire drawing is accomplished with ultrasonic vibration of single or double dies longitudinally in the direction of the draw. During one vibratory cycle, swaging is said to occur as the die moves in one direction, and polishing as it moves in the opposite direction. Claimed advantages include friction reduction between die and wire, increased drawing speed, greater reduction per draw, increased strength and/or ductility, and mechanical removal of impurities.

P15. Gutterman, R. P. (Engineering Research Associates, Inc.), "Method and Apparatus for Forming Wire and the Like." U.S. Patent 2,638,207, May 12, 1953 (filed Nov. 17, 1947).

Ultrasonic wire drawing is accomplished using a magnetostrictive tube which supports the die at an antinode at its forward end and with a counterweight at the opposite end. The wire is threaded through the center of the tube, which is supported at its nodal region. Feed and takeup reels are positioned at nodal points on either side of the die. Pressurized lubricant is applied through the transducer tube. Stated advantages included improved surface finish, more uniform wire diameter, reduced force requirement, reduction of die heat and wear, and facilitation of die lubrication.

P16. Schulz, W., "Process and Apparatus for Deforming Longitudinal Workpieces, Such as for Tube Drawing, Under the Application of Vibrations." German Patent 955,943, Dec. 20, 1956 (filed May 23, 1950).

The patent concerns a process for forming longitudinal workpieces, as in tube drawing, in which the die and/or mandrel is excited to high-frequency vibration in the radial or tangential or axial mode. The process reduces friction between tool and workpiece, imparts a polishing effect to the surface, improves dimensional accuracy, and permits drawing of hard materials such as tungsten without cracking.

P17. Korshunov, V. I. and N. V. Korshunova, "Device for Drawing Wire Using Ultrasonics." USSR Patent 144,140, filed July 14, 1961.

The wire drawing apparatus consists of a magnetostrictive transducer attached to a conical coupler with a conventional nodal flange and incorporating at its smaller end a draw die rigidly clamped between flanges. Separate water cooling is provided for the die and for the transducer. A reverse drawing direction is proposed, i.e., through the die orifice back through a tube constituting a passageway through coupler and transducer. It is noted that such an arrangement provides uniform longitudinal cold working of the wire.

Tube and Wire Drawing

P18. Kumabe, J., "Apparatus for Drawing Wire Through a Die Applying Thereto Supersonic Torsional Vibration Energy." Japanese Patent Publication 10612/1961, July 15, 1961 (filed March 26, 1960).

Wire drawing is accomplished through a die which is ultrasonically vibrated in torsion while the wire is being drawn.

P19. Kumabe, J., "Method for Drawing Wire While Vibrating a Die in the Same Direction as the Drawing Direction." Japanese Patent Publication 12259/1961, Aug. 1, 1961 (filed March 26, 1960).

Wire drawing is accomplished through a die which is ultrasonically vibrated in the direction in which the wire is drawn.

P20. Uzawa, K. (Nippon Telegraph & Telephone Public Corp.), "Supersonic Drawing Die." Japanese Patent Publication 1569/1962, May 9, 1962 (filed Aug. 11, 1960).

Ultrasonic drawing is accomplished while the draw die is vibrated in a direction normal to the direction of the draw.

P21. Moseev, V. F., O. P. Sukhanov, and B. V. Makarov, "A Vibrator for Drawing Wire With the Application of Ultrasonics." USSR Patent 158,555, filed Dec. 4, 1962.

In an ultrasonic wire drawing device consisting of a transducer-coupling system to which the die is attached, it is proposed that the die be installed so that its axis makes an acute angle with the axis of the transducer-coupling, to simplify construction and facilitate threading of the wire through the die. A nodal flange is provided on the coupler, and cooling water flows through the tranducer housing.

P22. Pavlov, A. M., I. N. Nedovizii, R. G. Trifonova, and S. I. Pegrukhi, "Process for Wire Drawing With the Application of Ultrasonics." USSR Patent 167,483, Jan. 18, 1965 (filed April 5, 1962).

In ultrasonic wire drawing, maximum reduction in draw force is obtained when the distance between the draw die and the take-up roll is adjusted to a multiple of a half-wavelength at the ultrasonic frequency.

P23. Boyd, C. A., J. B. Jones, and N. Maropis (Aeroprojects Inc.), "Vibratory Energy Method and Apparatus." U.S. Patent 3,209,572, Oct. 5, 1965 (filed June 21, 1963).

Tube and Wire Drawing

Wire drawing is accomplished with ultrasonic vibration of the die in the axial direction. The process may be applied to multistage drawing wherein each successive die is ultrasonically activated. Programmed ultrasonic power application may be desirable. The process is said to increase cross-sectional area reduction per pass, decrease draw force, increase draw speed, reduce the tendency to wire breakage, and facilitate drawing of wire heretofore difficult or impossible to draw.

P24. Boyd, C. A. and H. Kartluke (Aeroprojects Inc.), "Method and Apparatus Using Vibratory Energy." U.S. Patent 3,209,573, Oct. 5, 1965 (filed Aug. 19, 1963).

In ultrasonic drawing of tubing or wire, periodic dips in drawing tension at constant draw speed have been observed. Such dips may be eliminated by utilizing one oscillating die and a second non-compliant die spaced from the first die by an odd multiple of 1/4-wavelengths. In tube drawing, this arrangement may be used with an ultrasonically activated plug to define the annular passageway through which the tube is drawn; both the plug and the first die may be activated, or an activated plug may be used with two inert dies.

P25. Boyd, C. A. (Aeroprojects Inc.), "Apparatus and Method Applying Vibratory Energy." U.S. Patent 3,209,574, Oct. 5, 1965 (filed Nov. 4, 1963).

An improved method and apparatus for tube drawing consists of a floating plug system for drawing with an ultrasonically activated die and without joining the plug to the vibratory energy source. The floating plug has a length equal to an integral number of half-wavelengths; one end is disposed in the die orifice and the other end on the side of the die opposite the pulling means. This arrangement can be used for continuous drawing of long lengths or coils of tubing.

P26. Boyd, C. A., J. B. Jones, H. Kartluke, and H. L. McKaig (Aeroprojects Inc.), "Apparatus Utilizing Vibratory Energy." U.S. Patent 3,212,312, Oct. 19, 1965 (filed June 21, 1963).

Ultrasonic drawing of articles including tubes is accomplished with ultrasonic activation of the die and separate ultrasonic activation of the plug, making it possible to achieve results that can not be realized by activation of the die alone or of the plug alone. Advantages are said to include greater cross-sectional area reduction per pass, increased draw speed and/or lower drawing force, improved surface finish, and the ability to draw materials and/or articles heretofore difficult or impossible to draw. In addition, dies and plugs are readily interchangeable, electrical equipment may be located remoted from the die, and maintenance and setup of the equipment are simplified.

P27. Boyd, C. A., J. B. Jones, H. Kartluke, and H. L. McKaig (Aeroprojects Inc.), "Tube Drawing Apparatus Employing Vibratory Energy." U.S. Patent 3,212,313, Oct. 19, 1965 (filed June 21, 1963).

An ultrasonic plug drawing system for tube drawing is proposed wherein a transducer-coupling system and acoustic transmission element are coupled to the plug, the plug is partially disposed in the die orifice, and a vibratory antinode occurs in the portion of the plug located within the die. The vibratory energy is transmitted axially through the plug.

P28. Schmid, E., K. Lintner, D. Oelschlagel, and B. Weiss, "Process for Facilitating Chipless Draw Forming by Sonic or Ultrasonic Energy." Swiss Patent 418, 269, Aug. 15, 1966 (filed March 10, 1965; priority in Austria Sept. 8, 1964).

Ultrasonic drawing as of wires is accomplished with vibration of the die in a direction perpendicular to the direction of the draw and with a machine element such as a die holder located at a vibratory node. With wires of lead, iron, and aluminum, draw forces were reduced in the range of 37-62%. The process also permits increase in the area reduction achievable with a single draw.

P29. Maropis, N. (Aeroprojects Inc.), "Method and Apparatus Applying Vibratory Energy." U.S. Patent 3,295,349, Jan. 3, 1967 (filed Oct. 4, 1965).

In tube drawing with a floating plug and an ultrasonically activated die, improved results are obtained using a plug having a length equal to an odd integral number of 1/4-wavelengths of sound in the material at the operating frequency. The plug has one end in the die orifice and the other end on the side of the die opposite the pulling end, the plug being non-compliant at the end located in the die orifice.

P30. Fuchs, E. O., R. F. Jack, and K. M. Olsen (Bell Telephone Labs., Inc.), "Ultrasonic Wire Drawing." U.S. Patent 3,342,050, Sept. 19, 1967 (filed May 26, 1965).

Ultrasonic wire drawing is carried out with both wire and die immersed in a liquid contained in a tank. The liquid is ultrasonically excited by transducers mounted on the tank lid. The activated liquid acts as lubricant and coolant and provides the wire with an unusually high-quality, smooth surface finish.

Tube and Wire Drawing

P31. Goble, R. W. (Calumet & Hecla, Inc.), "Electrostrictive Effect in a Transducer for Drawing Wire, Rod or Tube." U.S. Patent 3,434,329, March 25, 1969 (filed Dec. 27, 1965).

A structure for radially contracting and expanding a die for drawing wire, rod, or tube includes an annular member for holding the draw die, surrounded by at least one radially polarized electromechanical transducer, which in turn is surrounded by a second annular member through which an electrical signal is transmitted to the transducer. If desired, a second transducer can be installed on the die radially outward of the first transducer.

P32. Kendall, L. A. (Ohio State University), "Wire Drawing Apparatus and Method Using Intermediary Impact Device." U.S. Patent 3,613,422, Oct. 19, 1971 (filed April 28, 1969).

A wire drawing apparatus utilizes a wire drawing die and an axially apertured piezoelectric electromechanical transducer and transmission line, with apertures axially aligned with the die orifice and transmitting vibratory energy to the die by impact coupling. The free-floating die is supported by flexible diaphragms, and its entrance is on the side opposite the ultrasonic system. Such an arrangement provides smooth wire surface finish, reduces by a factor of 10 to 100 the required drawing force, and increases die life.

P33. Isobe, K., H. Tsuji, S. Kawahata, E. Mori, and K. Ito (Nippon Kokan Kabushiki Kaisha), "Method and Apparatus for Cold Drawing Metal Tubes." U.S. Patent 3,657,910, April 25, 1972 (filed March 9, 1970; priority in Japan Sept. 16, 1969).

In ultrasonic tube drawing, stable vibratory energy is obtained by fitting a plurality of small transducers on the periphery of a resonant flange coupled through a transmitting member to a tube drawing mandrel. Vibrations in the radial direction are converted to axial in the transmitting member and thence into the mandrel and plug. Several such disk-shaped flanges can be installed on the transmitting member to further increase available vibratory energy. The amplitude of the system is detected, and deviations from a predetermined set value are corrected.

Extrusion

P34. Jones, J. B. (U.S. Atomic Energy Commission), "Vibratory Squeeze-Forming of Metals in the Solid State and Apparatus Therefor." U.S. Patent 3,002,614, Oct. 3, 1961 (filed Dec. 13, 1956).

Extrusion

The extrusion of solid-state metals may be accomplished with or without lubricant by simultaneously applying pressure and ultrasonic energy to the metal through some portion of the extrusion apparatus, as through the housing and/or die and/or ram via one or more transducer-coupling systems. The apparatus may be vibrated axially or flexurally or radially. Possible advantages include greater area reduction, increased extrusion rate, reduced force, improved surface finish, and smaller and more economical equipment.

P35. Bodine, A. G., "Sonic Method and Apparatus for Extruding Flowable Materials." U.S. Patent 3,169,589, Feb. 16, 1965 (filed Aug. 21, 1958).

This patent deals generally with earth drilling and core taking. Four claims, however, deal with extrusion of fluidizable materials including solid and powdered metals wherein the material flows through an open-ended tube excited to vibration by any known means so that the material being extruded is fluidized and flows more easily through the tube. The tube may be excited to longitudinal or torsional vibration.

P36. Jones, J. B. (Aeroprojects Inc.), "Ultrasonic Extrusion Apparatus." U.S. Patent 3,203,215, Aug. 31, 1965 (filed June 5, 1961).

Apparatus is provided for applying ultrasonic energy to a material being extruded through a die under high pressure. The die is ultrasonically activated in the direction of emergence of material from the die and is supported by means of a force-insensitive mount to minimize energy loss under the applied pressure. Ultrasonic extrusion with this apparatus is applicable to metallic and other materials, effecting reduced extrusion loads and improved surface finish.

P37. Evans, S. O. (Babcock & Wilcox Co.), "Method and Apparatus for Vibrating Squeeze-Forming of Metals." U.S. Patent 3,274,812, Sept. 27, 1966 (filed July 1, 1964).

Reduction in cross-sectional area of a solid object is accomplished by applying axial pressure to the object to force it through a die and simultaneously applying transverse vibratory energy from two or more transducers which are angularly disposed with respect to each other and are vibrated out of time phase with each other in order to impart torsional vibration to the member. The process reduces the required force, increases the processing speed, and improves the quality of the finished product.

P38. Busselmeier, O., "Process for the Production of Rolled Material." German Patent 930,201, July 11, 1955 (filed Nov. 23, 1951).

Rolling of materials is accomplished by two opposing tools, such as rolls or pressure plates, which press on the material and vibrate in the feed direction at different vibratory amplitudes, or perpendicular to the feed direction and parallel to the material surface, or in rotary motion. Force, frequency, and phasing of the vibratory amplitude are selected according to the specific application. The process makes possible enhanced densification of the material, modification of its ductility, homogenization, and increased rolling rate.

P39. Karron, J., G. N. Landis, and L. Robbins (Baldwin-Lima-Hamilton Corp.), "Reducing the Cross Section of Material." U.S. Patent 2,995,050, Aug. 8, 1961 (filed April 27, 1959).

In the cross-sectional reduction of solid metal shapes by compression rolling, the tension-pulling means that engages the leading or trailing edge may be ultrasonically activated, either through clamps or through pinch-rolls. The material deformation resistance is thus reduced, improving the accuracy and efficiency of rolling, reducing bearing friction and wear, and reducing force requirements for rolling.

P40. Jones, J. B. (Aeroprojects Inc.), "Vibrating Roll and Method." U.S. Patent 3,096,672, July 9, 1963 (filed July 28, 1960).

Cross-sectional reduction of metals by rolling is accomplished with an apparatus wherein at least one of the rotating rolls is an acoustical coupling member adapted to vibrate in a direction parallel to the roll rotational axis or parallel to the workpiece surface or perpendicular to the applied force direction. Two opposing rolls may be vibrated 180° out of phase. The process effects reduction in required rolling forces, reduction in metal grain size, and improvement in metal mechanical properties.

P41. Gross, L., "Method of Ultrasonic Drawing of Sheet Metal." U.S. Patent 3,318,129, May 9, 1967 (filed March 29, 1965).

Ultrasonic rolling of sheet metal is accomplished between a set of rollers and ultrasonic energy in the order of 20 kHz is applied through one of the rollers, which has a smaller diameter than the other rollers. The process increases the thickness reduction per pass, reduces the number of passes required for a given thickness, minimizes the necessity for annealing, and produces a sheet with a smooth outer surface free from internal stresses caused by repeated steps of rolling and annealing.

Rolling

P42. Balamuth, L. (Cavitron Corp.), "Apparatus for Altering the Cross-Sectional Shape of a Plastically Deformable Workpiece Using High Frequency Vibrations." U.S. Patent 3,495,427, Feb. 17, 1970 (filed April 5, 1965).

An ultrasonic apparatus is proposed for altering the cross section of a workpiece as in rolling. The workpiece is continuously advanced through an opening formed by a multiple-member die, at least one member of which vibrates in a plane perpendicular to the direction of travel of the workpiece. The vibratory energy softens the workpiece and reduces frictional resistance between workpiece and die members.

Straightening and Stress Relief

P43. Peterson, A. K. (Longren Aircraft Co.), "Methods and Apparatus for Straightening Integrally Reinforced Metal Extrusions." U.S. Patent 2,767,767, Oct. 23, 1956 (filed June 6, 1952).

A structural panel with integral longitudinal stiffening ribs, as for an aircraft skin surface and the like, may be straightened by stretching the panel as it is advanced between a pair of appropriately contoured rollers and simultaneously applying high-frequency vibration through one or both of the rollers. The vibration provides a means for stressing the metal beyond its yield point in order to eliminate internal stresses and provide a smooth, flat, aerodynamic surface.

P44. Vorob'ev, V. G. and I. Kh. Lokshin, "Process for Thermal Treatement of Metal Objects." USSR Patent 159,876, Jan. 14, 1964 (filed Jan. 30, 1963).

The process described involves heating a metal object to its annealing or aging temperature and simultaneously subjecting it to mechanical vibrations (no frequency or frequency range is mentioned). The patent claims that, as a result of this process, the workpiece will experience intensified relief of internal stresses and minimized dimensional change.

P45. Jacke, S. E. (Branson Instruments, Inc.), "Ultrasonics." U.S. Patent 3,274,033, Sept. 20, 1966 (filed Aug. 12, 1963).

Residual stress in solids, and particularly in weldments of titanium alloys after solidification, may be relieved by applying ultrasonic energy at a frequency of 20 kHz to the weldment at room temperature. An ultrasonic transducer is manually pressed against the weldment with an intensity as high as possible without cracking or otherwise injuring the material.

Straightening and Stress Relief

P46. Langenecker, B. (U.S. Secretary of the Navy), "Method for Strengthening Metals." U.S. Patent 3,276,918, Oct. 4, 1966 (filed July 11, 1963).

Workhardening of a solid metallic body may be achieved by subjecting the body to ultrasonic oscillations having a pressure amplitude sufficient to activate lattice dislocations and cause them to migrate and to form locked lattice defects. Simultaneously the body may be subjected to a strain below its elastic limit.

P47. Dickey, C. [illegible]. and R. A. Bland (Sutton Engineering Co.), "Roller Leveler and Method of Leveling." U.S. Patent 3,678,720, July 25, 1972 (filed Aug. 13, 1970).

Leveling or flattening of sheet or strip materials without stressing the material is accomplished by superimposing high-frequency dynamic stresses on static stress in tension and/or bending, whereby residual stresses are redistributed and the leveling process is facilitated. The apparatus consists of a hollow cylindrical roller within which ferroelectric transducers are supported and containing a liquid through which radial vibrations are directed, causing the roll to vibrate in a bell mode.

Powder Metallurgy

P48. Dawihl, W. and H. Franssen (General Electric Co.), "Method for Producing Sintered Hard Metal from Pulverulent Materials." U.S. Patent 2,246,165, June 17, 1941 (filed May 27, 1939; priority in Germany Aug. 27, 1938).

Intimate intermixing of powdered materials is obtained by subjecting the mixture to the action of ultrasonic vibrations within a mixing device and/or in a press mold. For example, in the production of tungsten carbide, a mixture of tungsten and carbon is mixed as thoroughly in 60 min at 350 kHz as in 24 hr in a ball mill without ultrasonic activation. The formation of bridges and cavities and depositions of non-uniform density are thus eliminated.

P49. Scharf, H. (Maschinenfabrik Augsburg-Nurnberg A.G.), "Process for Consolidation of Powders in Molds." German Patent 824,021, Oct. 31, 1951 (filed July 2, 1949).

Consolidation of dry metal or ceramic powders in molds, as in the fabrication of rotor blades for gas turbine engines or other machine parts, is accomplished with ultrasonic vibration of the powder through a piston acting on the surface. With suitable orientation of the ultrasonic source, the workpiece can be given selective directional characteristics. The solid body thus produced can be removed from the mold, worked, and heat-treated.

Powder Metallurgy

P50. Sorensen, E. and H. Scharf (Maschinenfabrik Augsburg-Nurnberg A.G.), "Molding Method." U.S. Patent 2,645,836, July 21, 1953 (filed Dec. 29, 1949).

A method is proposed wherein dry powdered materials, such as ceramics, are compression-molded without binder by introducing ultrasonic energy through the mold walls in one or more directions requiring maximum strength in the finished article. The ultrasonic transmission is continued after the compression force is released. This produces a self-sustaining article ready for firing.

P51. Hagen, H. W. (Soest-Ferrum Apparatebau GmbH), "Process and Apparatus for the Treatment of Pasty Materials, Especially Ceramic Compositions." German Patent 907,033, Feb. 4, 1954 (filed Nov. 15, 1951).

In the forming of paste-like materials such as ceramics by extrusion or pressing, the material is subjected to ultrasonic vibrations at a frequency above 20 kHz during or after pressing, in order to improve the structural homogeneity of the composition and to eliminate cracks and fissures. The frequency may be variable or may be tuned to the natural frequency of the material. Various arrangements for introducing the vibratory energy are proposed.

P52. Bodine, A. G., "Sonic Method for Powdered Metal Molding." U.S. Patent 2,815,535, Dec. 10, 1957 (filed June 26, 1953).

In the fabrication of powdered metal objects in complex molds, the introduction of vibratory energy, preferably in the range of 20-50 kHz, during compression agitates the powder particles, causing them to flow into all portions of the mold, and also effects local heating at interparticle contact points, producing bonds between the particles. The resulting body has increased strength and ruggedness and can be handled without damage.

P53. Bartells, H. and H. Fritsch (International Standard Electric Corp.), "Process for Connecting a Tantalum Electrode Pin to an Electrode Body." U.S. Patent 2,819,961, Jan. 14, 1958 (filed Dec. 10, 1953; priority in Germany Dec. 20, 1952).

A tantalum electrode pin is attached to a powdered tantalum electrolytic condenser by pressing the pin into the powder, applying heat for sintering the powder, and simultaneously applying heat and ultrasonic energy through the pin to improve welding. This eliminates oxide coatings and provides improved electrical contact.

Powder Metallurgy

P54. Marshall, A. F. (Agricola Metals Ltd.), "Production of High Density Compacts." U.S. Patent 3,231,373, Jan. 25, 1966 (filed Oct. 15, 1962; priority in Great Britain Oct. 13, 1961).

High-density, low-porosity powder compacts are produced by cyclic reciprocation of the punch. In a preferred embodiment, the powder is subjected to ultrasonic vibration while it is being fed to the container. The vibrations may be applied to the punch or through the wall or base of the powder container.

P55. Kartluke, H., H. L. McKaig, and W. B. Tarpley (Aeroprojects Inc.), "Process for Producing Elongated Objects from Powdered Metals." U.S. Patent 3,608,178, Sept. 28, 1971 (filed Nov. 25, 1969).

One or more powdered metals, elemental or alloy, are mixed with a plasticizer and binder, and the mixture is extruded into elongated hollow or solid shapes using an extruder equipped with an ultrasonically activated die, which reduces the required extruding force and permits reduction in the amount of plasticizer and binder, so that a higher density product is obtained and less shrinkage and distortion occur on drying and sintering. The shape is subsequently cold worked, as by drawing on an ultrasonically activated drawbench, to increase its density and mechanical properties.

Miscellaneous Metal Forming

P56. Riedl, A., "Stretch Drawing Process for Sheets." German Patent 729,429, Dec. 16, 1942 (filed March 11, 1941).

The stretch-drawing of light metal alloys over form blocks is accomplished with mechanical vibration of the block and/or the workpiece. Such excitation decreases friction between block and workpiece, equalizes stresses, permits greater draw depth, and reduces required forces. The type of vibrator, as well as vibratory mode, frequency, and amplitude, depend among other things on workpiece material and shape.

P57. Vang, A. (Continental Can Co., Inc.), "Material Forming and Drawing With the Aid of Vibration." U.S. Patent 2,393,131, Jan. 15, 1946 (filed Aug. 21, 1942).

A method and apparatus are proposed for deep drawing of shells and tubular members wherein a movable punch and/or a stationary die are subjected to high-frequency vibration either axial or transverse to the longitudinal axis of the equipment. The stated advantages include reduced friction, greater depth per draw, increased forming rate, and extended die life.

P58. Balamuth, L. and A. Kuris (Cavitron Ultrasonics Inc.), "Metal Forming." U. S. Patent 3,201,967, Aug. 24, 1965 (filed Feb. 23, 1960).

Die forming, as in dimpling, of metals that are ordinarily difficult to form is accomplished by ultrasonic axial activation of at least one of the dies at a frequency in the range of 1-100 kHz while simultaneously exerting static force between the dies. The combined action of vibration and force reduces static force requirements, eliminates defects and failures that may occur in shaping brittle metals, exerts a forging action on the metal, and reduces surface friction at the die/metal interface.

P59. Falcioni, J. G. (Boeing Co.), "Riveting Apparatus." U.S. Patent 3,292,413, Dec. 20, 1966 (filed Oct. 21, 1963).

The patent covers a method for ultrasonically setting rivets in which opposed transducers are positioned against the two ends of the rivets, and vibratory energy above 20 kHz is applied to set the rivet. The transducers may be operated in a programmed mode in phase or out of phase, at the same or different frequencies, or with variable frequency and amplitude. In portable units, clamping force may be applied manually. This eliminates the complexities of conventional riveters, increases production rates, improves reliability, reduces maintenance, and produces a more uniform product.

P60. Bitzer, A. H. (Illinois Coil Spring Co.), "Method and Apparatus for Simultaneously Cold Forming and Stress Relieving Metal Coils." U.S. Patent 3,323,340, June 6, 1967 (filed Feb. 17, 1964).

In the manufacture of coil springs, the normalizing process is eliminated and internal stresses are relieved by subjecting the material during forming to ultrasonic frequencies (20-100 kHz) of low amplitude during coiling of the spring without application of heat or electrical current and at lower cost than entailed in the normalizing process. The ultrasonic system can be adapted to a conventional spring coiling machine without substantial modification of the machine and without slowing down its production capacity.

P61. Bodine, A. G., "Sonic Method and Apparatus for Closed-Die Forging." U.S. Patent 3,382,692, May 14, 1968 (filed June 7, 1965).

A closed-die forging machine is provided in which the billet is located at the termination of a resonant acoustic circuit to which intense sonic energy is applied. The frequency is adjusted to accommodate impedance changes naturally occurring in the resonant circuit during forging. The sonic standing wave thus established in the workpiece while it is being forged greatly enhances its grain structure, freedom from porosity, and numerous other properties.

Miscellaneous Metal Forming

P62. Cwik, J. A. (Teledyne, Inc.), "Method and Apparatus for Bending Tubing." U. S. Patent 3,473,361, Oct. 21, 1969 (filed April 6, 1967).

To a tube-bending machine of conventional construction is added a high-frequency mechanical force generator coupled to tooling or workpiece to impart vibratory energy to the workpiece in the bending zone. Such activation renders the workpiece semi-plastic in nature to reduce resistance to bending and cause metal flow from inside to outside of the bend and minimize wall thickening and thin-out. The surface-wave effect reduces friction between tooling and workpiece. Further advantages include reduction in springback, elimination of lubricant, refined grain structure, minimized wrinkling, elimination of "orange-peel" effect, and lower bending forces.

P63. Balamuth, L. and T. Parisi (Cavitron Corp.), "Methods and Apparatus for Assembling Parts Together by Ultrasonic Energy." U.S. Patent 3,483,611, Dec. 16, 1969 (filed Aug. 12, 1966).

In the assembly of components by heading or staking operations using a rivet-like member, application of high-frequency mechanical vibrations (1-100 kHz) applied to the member in a direction parallel to the direction of static force application causes the extended portion of the member to soften and form a head with lower applied static force and without heat application.

P64. Turner, P. (Kahr Bearing Corp.), "Method of Treating Bearings With Ultrasonic Vibrational Energy." U.S. Patent 3,581,362, June 1, 1971 (filed June 12, 1969).

Mechanical vibrations introduced into the race of a swaged spherical bearing stabilize the race, reduce required swaging force, eliminate springback of race from inner bearing member, and produce desired preload torque between inner and outer bearing members. One claim involves rotating the inner race relative to the outer race, monitoring required rotational torque, and discontinuing vibration when a predetermined torque value is achieved.

C. METAL REMOVAL

General

P65. Hayes, H. C., "Impact Tool." U.S. Patent 1,966,446, July 17, 1934 (filed Feb. 14, 1933).

Impact tools such as chisels or riveting hammers are ultrasonically activated in the longitudinal mode at high frequency (preferably above the audible range) to increase the rate of material removal, increase accuracy, and eliminate the physical discomfort associated with use of the device. The vibration may be generated by magnetostrictive or piezoelectric means, located within the handle.

P66. Perthen, J., "Process for Chip Machining of Brittle Materials." German Patent 663,454, Aug. 6, 1938 (filed March 26, 1937).

Chip machining processes, such as turning, sawing, milling, planing, and boring, are facilitated by exciting the tool and/or workpiece to vibration at an amplitude exceeding the endurance limit of the material and in a sinusoidal or rectangular motion. Material removal is accelerated and greater accuracy achieved with lower applied forces than in conventional processes.

P67. Round, H. J. (Marconi's Wireless Telegraph Co. Ltd.), "Improvements in Graving or Like Tools Having a Vibrating Head." British Patent 553,176, May 11, 1943 (filed Nov. 7, 1941).

Improved cutting or engraving of hard materials is obtained by using a cutting tool or point of hard steel or diamond, for example, attached to a magnetostrictive transducer excited to resonance preferably in the range of 10 to 80 kHz. A steel coupler may be inserted between transducer and tool to increase amplitude. Alternately, the transducer is attached to the workpiece and a non-vibrating tool is used, or vibrations are transmitted to the tool through one or more flexible metal wires.

P68. Bodine, A. G. (Calpat Corp.), "Portable Cutting Tool." U.S. Patent 2,384,435, Sept. 11, 1945 (filed Dec. 18, 1942).

Sonic or ultrasonic vibration is applied to portable cutting tools, with the source of driving energy remotely located and the vibration being introduced through an elastic medium such as oil or water located in a flexible conduit attached to the tool, providing a light-weight, compact device with relatively few moving parts. This may be used, for example, for driving a metal-cutting saw or blade, file, punch, knife, riveting tool, hammer, polishing or abrading tool, or the like. The vibratory motion can be effected at right angles or any desired angle to the axis of the tool.

P69. Farrer, J. O., "Improvements in or Relating to Cutting, Grinding, Polishing, Cleaning, Honing, or the Like." British Patent 602,801, June 3, 1948 (filed April 14, 1945).

This improved method of material removal comprises subjecting the solid body to impulses of abrasive material in finely comminuted form oscillating at high frequency. The abrasive particles may be suspended in a liquid medium applied between tool and workpiece or embedded in the tool itself. The process permits cutting, grinding, etc. of hard materials impossible to process by conventional means.

P70. Rosenthal, A. H. (Scophony Corp. of America), "Machine for Mechanically Working Materials." U.S. Patent 2,452,211, Oct. 26, 1948 (filed Oct. 17, 1944).

The invention comprises a method and machine for boring, sawing, lapping, and the like in which the tool is caused to vibrate at high frequency in a direction parallel to the path of material removal. The vibratory source may be a magnetostrictive rod attached to the tool holder, or a piezoelectric source which transmits vibration through a plate into liquid in which standing waves are set up and thence to a diaphragm on which the tool holder is mounted. The tool may be used with abrasive powder or paste. A stream of liquid or gas directed onto the work removes particles carved out.

P71. Calosi, C. L. (Raytheon Manufacturing Co.), "Support for Vibratory Devices." U.S. Patent 2,632,858, March 24, 1953 (filed Nov. 16, 1950).

An ultrasonic tool consists of a half-wavelength laminated nickel vibrator connected to the tool by a tapered rod. A supporting tube, of 1/4-wavelength, telescopes the vibrator and secures it to the housing at its upper end. Because vibration is nil at the end of the support tube, there is no cavitation of cooling water flowing through the housing as occurs when a diaphragm is used for support. A working tool may be attached for drilling, abrading, or other purposes.

P72. Carwile, P. B. (Raytheon Manufacturing Co.), "Ultrasonic Vibratory Device." U.S. Patent 2,651,148, Sept. 8, 1953 (filed Nov. 23, 1949).

Ultrasonic oscillators for drilling regular or complex shaped holes, for grinding, cutting, polishing, and other applications, consist of a magnetostrictive member attached at an antinode (to minimize mechanical stress) to a resonant tapered horn of Monel, which amplifies the vibratory amplitude. The resonant support structure is at or near an antinode and the diaphragm is attached at a node to reduce losses of vibratory energy.

P73. Calosi, C. L. (Raytheon Manufacturing Co.), "Tool Chuck for Vibrating Devices." U.S. Patent 2,680,333, June 8, 1954 (filed March 16, 1951).

An ultrasonic machine tool consists of a magnetostrictive vibrator which drives a small tool through a solid tapered horn. A chuck is provided for attaching various tools to the small end of the horn. The sleeve of the chuck is made a half-wavelength long, and its cross-sectional area is preferably tapered at the same rate as the driving horn. Thus vibrational stresses applied to ends of the sleeve are minimized and there is little tendency for the threaded joint to loosen.

P74. Voronin, A. I. and A. I. Markov, "Method of Cutting Metal." USSR Patent 121,638, filed Jan. 12, 1956.

In cutting difficult-to-work materials such as heat-resistant steel, wherein the workpiece or the tool is subjected to vibratory motion, it is proposed that the vibrations be of ultrasonic frequency (10-30 kHz) and of small amplitude (0.01-0.03 mm) in order to reduce friction on the cutting surface of the tool and facilitate plastic deformation of the metal.

P75. Karlstrom, K. A. S., "Vibrator." U.S. Patent 2,730,902, Jan. 17, 1956 (filed Nov. 22, 1952).

The invention refers to vibrators of the kind where the vibrations are generated by the rolling of a roll body secured on a resilient spindle inside a hollow cylindrical impulse body. Rotational motion develops vibration at a frequency that can reach into the ultrasonic range. The impulse member may be provided with tools of various kinds, for example, a spatula, chisel, knife, grinding trundle, impact bore, and the like.

P76. Dench, E. C. (Raytheon Manufacturing Co.), "Apparatus for Precision Contouring." U.S. Patent 2,804,725, Sept. 3, 1957 (filed May 17, 1954).

The apparatus, based on the magnetostrictive device of U.S. Patent 2,632,858 (P71), incorporates a tool having a peripheral cutting edge of extreme thinness, the cutting edge forming a closed loop, making it possible to cut an article having a large cross-sectional area. The workpiece is fed toward the tool as cutting proceeds. Alternatively, a single cutting edge may be used and the workpiece is translated to permit the desired contour to be formed.

P77. Findley, H. J., "Apparatus for Cutting Material." U.S. Patent 3,003,372, Oct. 10, 1961 (filed Sept. 29, 1959).

Metal removal by a rotating tool, as in twist drilling, machining, cutting, reaming, boring, and the like, is facilitated by ultrasonic activation of the tool. Stated benefits include chip breaking, improved cooling by the intermittent removal of pressure from the workpiece, extended tool life, increased rate of metal removal, and lower power consumption. Various embodiments are described.

P78. Harris, W. T. (Harris Transducer Corp.), "Magnetostrictive Actuator." U.S. Patent 3,007,063, Oct. 31, 1961 (filed Jan. 10, 1958).

The magnetostrictive transducer system incorporates two interconnected stacks of laminated magnetostrictive material having differing magnetostriction coefficients and each having a lever bar brazed thereto at right angles. A mechanical system such as a drill or saw may be attached at right angles to the lever, thus parallel to the direction of vibration. The two transducers produce clockwise rotation of the levers and linear displacement in the mechanical system.

P79. Kleesattel, C., L. Balamuth, and A. Kuris (Cavitron Corp.), "Acoustically Vibrated Material Cutting and Removing Devices." U.S. Patent 3,076,904, Feb. 5, 1963 (filed Aug. 29, 1958).

An ultrasonic machining tool comprises a tubular casing containing an energizing coil for the transducer, a removable insert which includes the transducer and the coupler attached thereto, a tubular retainer and sealing ring for retaining the insert within the casing, and a second sealing ring attached to the transducer-coupling at a vibratory node in snug contact with both casing and insert. The insert may thus be readily separated from the housing, and the housing is essentially free from vibration. Various types of worktools may be attached, as for drilling, boring, cutting, reaming, polishing, shaping, etc.

P80. Kleesattel, C., L. Balamuth, and A. Kuris (Cavitron Ultrasonics, Inc.), "Magnetostrictive Vibratory Apparatus." U.S. Patent 3,100,853, Aug. 13, 1963 (filed Nov. 2, 1959).

An improved, high-efficiency vibrator assembly, to which may be attached a tool for boring, cutting, chipping, etc., with or without abrasive slurry, consists of a compact stack of magnetostrictive laminates of arcuate shape, with concave-convex curvature in the range preferably of 25-45°. The stack is removably inserted in a housing containing the energizing coil and is supported by a collar in one end of the housing. An impedance transformer is rigidly bonded to one end of the stack, and supporting studs are located at vibratory nodes. Cooling air is blown through the housing to dissipate heat.

P81. Kleesattel, C., L. Balamuth, and A. Kuris (Cavitron Ultrasonics Inc.), "Ultrasonic Vibration Generator." U.S. Patent 3,113,225, Dec. 3, 1963 (filed June 9, 1960).

This patent concerns a vibration-transmitting member having one or more large dimensions in planes parallel to the input and output surfaces wherein a plane wave front is obtained over the entire output surface in response to the introduction of vibrations at suitably spaced locations on the input surface. Slots are introduced across the nodal plane and perpendicular to the output surface to break up Poisson's couplings and insure uniform output. Such a device can be used, for example, for cutting, gang drilling, machining, and the like.

P82. Balamuth, L. and A. Kuris (Cavitron Ultrasonics Inc.), "Magnification of the Amplitude of Magnetostrictive Radial Vibrations." U.S. Patent 3,139,543, June 30, 1964 (filed April 25, 1962).

In order to achieve amplification of radial vibrations for operations such as grinding, honing, machining, and the like, the coupler is provided with an acoustically designed disk or ring mounted at a vibratory node and having radial slots separating this member into diametrically opposed sectors of different masses, wherein the vibrations are magnified in the sector having the smaller mass. The slotted member may be part of a magnetostrictive transducer.

P83. Ustyantsev, A. A. and B. K. Mechetner (Eksperimentalny Nauchno-Issledovatelsky Institut Metallorezhutschikh Stankov), "Apparatus for Control of Tool Feed Force on Ultrasonic Machine Tools." Swiss Patent 464,583, Oct. 31, 1968 (filed Jan. 23, 1967).

Tool feed force on ultrasonic machine tools is controlled by means of a counterweight on a balance beam, with a chassis for moving the counterweight along the beam and a potentiometer with a movable contact connected to the chassis.

P84. Riley, R. H. and J. W. Wood (Black and Decker Manufacturing Co.), "Portable Sonic Hand Tool with Means for Reducing the Effects of Operator Bias Upon Transducer Output and Efficiency." U.S. Patent 3,485,307, Dec. 23, 1969 (filed Feb. 13, 1968).

The invention provides a means for eliminating adverse effects or operator bias on the output and efficiency of a transducer mounted in a portable sonic or ultrasonic hand tool, maintaining relative axial positioning of the tool and the impedance transformer with respect to each other, and incorporating a resilient mounting means which tends to neutralize rebound effects of the tool from the work. The transducer, when energized, exhibits a first

high frequency and a second lower frequency which causes the tool to vibrate. The device may be used for drilling, gouging, and the like.

P85. Eksperimentalny Nauchno-Issledovatelsky Institut Metallorezhutschikh Stankov, "Device for Controlling the Pressure of an Ultrasonic Tool on an Article Being Machined." British Patent 1,140,992, 1969 (filed 1967).

In an ultrasonic machine tool, the pressure of the tool on the workpiece is controlled by a counterweight whose position in a guide can be varied to vary the pressure via a lever system. A potentiometer governed by the counterweight position gives the pressure reading on a meter.

P86. Ustyantsev, A. A. and B. K. Mechetner, "Device for Controlling the Pressing Force of an Ultrasonic Tool Against an Article Being Machined." U.S. Patent 3,492,847, Feb. 3, 1970 (filed Dec. 6, 1966).

Devices are proposed for controlling the force with which an ultrasonic tool is pressed against a workpiece, which is fitted with a load counterweight disposed on a rocker, and a potentiometer disposed beside the rocker with a movable contact fastened to the mechanism for displacement of the load counterweight along the rocker.

P87. Riley, R. H. (Black and Decker Manufacturing Co.), "Sonic Tool With Generally Undamped Mounting of Nodal Portion of Transducer." U.S. Patent 3,511,323, May 12, 1970 (filed Feb. 23, 1968).

A tool for drilling and the like houses an ultrasonic transducer which is mounted at its nodal position inside a housing to accommodate a relatively undamped movement of the nodal portion relative to the housing and in the direction of cyclic deformation of the transducer. As a result, a relatively lower frequency oscillation may be superimposed on the higher frequency oscillation of the transducer for improved results in a given application.

Turning

P88. Gutterman, R. P. (Engineering Research Associates, Inc.), "Vibrating Tool." U.S. Patent 2,553,251, May 15, 1951 (filed Jan. 2, 1947).

A transducer-coupling system for mounting on a lathe supporting system or other machine tools is provided with an improved mounting clamp designed to take up cutting forces in shear and vibratory forces in bending so as to prevent transverse tool movement. The clamp comprises multiple elongated strips of material arranged circumferentially about the system at the tool juncture and attached to a diaphragm which connects the transducer to the housing; air passageways are provided for cooling.

Turning

P89. Williamson, D. T. N. (Ferranti, Ltd.), "Improvements Relating to Turning and Planing Machining Processes." British Patent 714,860, Sept. 1, 1954 (filed Oct. 19, 1951).

In single-point cutting, as in turning or planing, machining accuracy is improved by vibrating the tool in the cutting direction, or in the plane of the workpiece surface, or in the direction of the cutting axis. The apparatus consists of a cutting tool secured to an exponentially tapered brass member welded to a magnetostrictive transducer. The vibratory frequency should not coincide with the resonant frequency of the workpiece or its supports and should not be an exact multiple of the rotational speed. Two vibrators, perpendicular to each other, may be used with a single tool, with the apexes of the tapered members secured together just behind the tool.

P90. Jones, J. B. (Aeroprojects Inc.), "Transducer Coupling System." U.S. Patent 3,466,970, Sept. 16, 1969 (filed July 6, 1965).

An ultrasonic transducer-coupling system has a work-performing tip such as a lathe-cutting tool attached to it and spaced from the free end by an even whole number of 1/4-wavelengths. The system is supported at a location between the tool and the free end at a node spaced from the free end by an odd whole number of 1/4-wavelengths. Such a cantilever arrangement used in conjunction with a lathe provides advantages such as increased tool life, decreased tool forces, elimination of chatter, greater depth of cut, increased cutting speed, and/or improved surface finish.

P91. Maropis, N. (Aeroprojects Inc.), "Apparatus for Delivering Vibratory Energy." U.S. Patent 3,640,180, Feb. 8, 1972 (filed April 17, 1970).

A device for delivering vibratory energy to a work-performing tool is disclosed having one end connected to a vibration-generating means and providing for mechanical attachment and alignment of the tool at the work performing locale which is located at a vibratory antinode in the system. The toolholder is an integral part of the ultrasonic transmission system and does not constitute a mass load on the system. The system may be conveniently mounted on a lathe cross-feed table.

Drilling

P92. Bodine, A. G., "Method and Apparatus for Cutting into the Surface of an Article." U.S. Patent 2,445,934, July 27, 1948 (filed Nov. 3, 1942).

A new method is proposed for cutting operations such as finishing, grooving, and particularly gun barrel rifling, wherein the cutter is

oscillated in the direction of the walls of the bore by sound waves from a few hertz up to many thousands of hertz. The sound waves may be transmitted through an elastic medium such as water. The cutter, which may be of the blade or point type or consist of one or more blocks of abrasive material, is activated through a short locus of motion and with relatively high peak velocities, providing increased cutting speed over other techniques. Rifling of a gun barrel, either of constant diameter or with tapered bore, can thus be accomplished with a single pass.

P93. Calosi, C. L. and P. B. Carwile (Raytheon Manufacturing Co.), "Ultrasonic Vibratory Devices." U.S. Patent 2,748,298, May 29, 1956 (filed March 15, 1951).

In the construction of ultrasonic drills, it is common practice to provide an impedance transformer whose cross section is reduced exponentially but remains solid and of the same geometrical shape. This patent describes a variety of rods whose solid cross-sectional area decreases more or less exponentially but whose cross-sectional shape changes. Initially solid and round or square at the transducer, it may gradually become hollow or rectangular or both, to accommodate the shape of the cutting tool. A hollow, half-wavelength tool of uniform section may be added to the tapered section.

P94. Bodine, A. G., "Torsional Vibration Sonic Drill." U.S. Patent 2,921,372, Jan. 19, 1960 (filed June 24, 1955).

Ultrasonic drilling, with or without abrasive particles, is carried out in the torsional mode to provide increased vibratory amplitude and for easier tip access to certain locations. For side cutting, the bar on which the drill tip is mounted can have a lateral arm containing the drill tool. The tool may have abrasive particles embedded in it. Various embodiments are described.

P95. Kleesattel, C., L. Balamuth, and A. Kuris (Cavitron Ultrasonics Inc.), "Methods and Means for Driving Small Diameter Shafts at High Rotational Speeds." U.S. Patent 3,058,218, Oct. 16, 1962 (filed May 7, 1959).

A high-speed rotational ultrasonic drill for small holes includes a driving element (transducer) in tangential contact with a journaled cylindrical body, generating combined longitudinal and flexural vibrations so phased as to produce unidirectional orbital or ovaloid cycles substantially normal to the radius of the cylindrical body. Holes larger than the tool diameter can thus be drilled and provided with undercuts or otherwise varied diameters. The device can be provided with tools for drilling, boring, cutting, polishing, and the like.

Drilling

P96. Legge, P., "Improvements in or Relating to Ultrasonic Machining of Hard Materials." British Patent 987,801, March 31, 1965 (filed Jan. 21, 1964).

An ultrasonic drill is provided with an abrasive-impregnated (preferably diamond dust) probe which is pressed against a rotating workpiece, particularly useful for drilling deep blind flat-bottomed holes in hard materials. The probe may be hollow and/or fluted to permit introduction of coolant liquid to flush away the machined particles. Such a drill provides faster penetration and more dimensionally accurate holes than ultrasonic slurry machining. The workpiece may be rotated in an offset manner to provide a trepanning operation. The tool may also be used to form annular grooves and for thread cutting by rotating the workpiece at right angles to the probe.

P97. Jakhimovich, D. F., I. F. Orlov, and L. G. Chechina (Osoboe Konstruktorskoe Buro po Proektirovaniju Sredstv Avtomatizatsii i Kontrolya i Elektroerozionnogo Oborudovania), "Process for Ultrasonic Boring of Solid Workpieces as Well as Apparatus for Carrying Out the Process." Swiss Patent 420,685, Sept. 15, 1966 (filed April 23, 1965).

In ultrasonic boring of materials such as diamond dies with a rotating tool, boring accuracy is substantially improved and power requirements decreased by subjecting the tool alternately to longitudinal and transverse vibrations. The tool is connected to two transducers which are alternately activated.

P98. Smith, E. W., "Twist Drill Drive." U.S. Patent 3,429,204, Feb. 25, 1969 (filed Aug. 23, 1967).

A means is provided for drilling deep holes in metals and other hard materials, particularly holes in which the ratio of depth to diameter may be in the order of 150:1. The system incorporates a pair of inertia elements interconnected by a torsion shaft with means for maintaining these inertia elements in torsional oscillation at the resonant frequency of the mechanism. An electromagnetic source and a frequency of 60 hertz are mentioned, although other sources and frequencies are useful. The arrangement provides a means for periodic withdrawal of the cutting edge from the surface in the hole to facilitate the removal of shavings and chips, resulting in more rapid and accurate drilling than otherwise possible.

P99. Legge, P. (United Kingdom Atomic Energy Authority), "Ultrasonic Machining Apparatus." U.S. Patent 3,482,360, Dec. 9, 1969 (filed Jan. 9, 1967).

The rate of tool feed in previous ultrasonic machining equipment was determined by the addition or removal of weights from a counterbalance opposing the machining load. An alternate apparatus is described which employs a

weighted hydraulic piston with a continuous but adjustable fluid bleed past the piston to act as a counterbalance to the machining load. This apparatus is said to constitute a more precise means of adjusting tool feed.

P100. Jugler, J. (Branson Instruments, Inc.), "Ultrasonic Drive Assembly for Machine Tool." U.S. Patent 3,561,462, Feb. 9, 1971 (filed Oct. 10, 1969).

An ultrasonic drive assembly is described which is said to be eminently suited for machining hard and brittle materials. This assembly is longer-lived than its predecessors in that it effectively decouples the antifriction bearings guiding the shaft from the shaft itself, which is vibrating ultrasonically. This is accomplished by using a lining of compliant, substantially non-resilient material between the shaft and the inner race of the antifriction bearing.

Grinding

P101. Comstock, G. E. and G. Crompton (Norton Co.), "Apparatus and Method for Grinding." U.S. Patent 2,695,478, Nov. 30, 1954 (filed Dec. 29, 1952).

Several magnetostrictive rods are embedded in a grinding wheel disk, with their axes parallel to or radial of the disk axis, so that they provide radial vibration in the direction of the disk plane and perpendicular to the disk axis, preferably with one node at the wheel axis so that standing waves are produced. Such an apparatus removes stock at a high rate, with minimum heating of the disk and reduced tool wear, and produces an excellent finish.

P102. Luthman, J. J. and R. N. Roney (Sheffield Corp.), "Machine Tool Device." U.S. Patent 2,858,652, Nov. 4, 1958 (filed Nov. 13, 1957).

An ultrasonic device is operated in conjunction with a grinding wheel of a cylindrical grinder to improve operating efficiency and increase material removal rate. The operating surface of the device conforms in shape to a section of the wheel and is placed in close proximity to the wheel. The ultrasonic energy induces cavitation in a coolant flooding the wheel and thereby loosens particles of work material from between abrading grains, eliminating the necessity for frequent wheel dressing.

P103. Hazelton, R. L. (Omni American Engineering Co.), "Magnetostrictive Grinding Machine." U.S. Patent 2,986,132, Jan. 17, 1961 (filed Sept. 18, 1956).

Grinding

A grinding wheel may be ultrasonically vibrated in a direction perpendicular to the usual peripheral wheel motion, using any of several described arrangements. Stated advantages are smoother and more rapid abrading, more efficient removal of workpiece particles from the abrading surface, and elimination of the need for subsequent grinding operations.

P104. Roney, R. N. (Sheffield Corp.), "Ultrasonic Grinding Apparatus." U.S. Patent 3,239,965, March 15, 1966 (filed Sept. 13, 1961).

An ultrasonic grinding device is proposed wherein the vibrations are transmitted axially through the rotating grinding wheel hub and are converted into radial vibrations in the grinding disk. The rate of cutting is thus increased without burning of the workpiece and with reduced wear on the grinding wheel. Hard-to-machine materials are more readily cut by this means.

P105. Kuris, A. and L. Balamuth (Cavitron Ultrasonics Inc.), "Ultrasonic Grinding and Honing." U.S. Patent 3,273,288, Sept. 20, 1966 (filed April 25, 1962).

Ultrasonic vibrations directed generally normal to workpiece surfaces are produced at the active periphery or surface of a grinding wheel, abrasive belt, or honing tool to achieve a high rate of metal removal while reducing heating of the workpiece and wear on the tool. The grinding wheel may be made of magnetostrictive material or the shaft carrying the wheel may be vibrated.

P106. Balamuth, L. and C. Kleesattel (Cavitron Ultrasonics Inc.), "Ultrasonic Cleaning Methods and Apparatus." U.S. Patent 3,321,871, May 30, 1967 (filed March 5, 1964).

The peripheral working surface of a grinding wheel may be kept substantially free of loosened abrasive grains and debris during grinding by means of an ultrasonic cleaning tool located in close proximity to the wheel periphery, together with means for drawing off a portion of the air within the gap and for introducing liquid capable of supporting cavitation within the gap.

Finishing

P107. Bodine, A. G., "Method of and Apparatus for Cutting and the Like." U.S. Patent 2,460,918, Feb. 8, 1949 (filed Dec. 12, 1942).

Fabricated metal objects may be provided with a highly polished surface which is extremely smooth and also with a uniformly peened surface by suspending the objects in a liquid containing abrasive or non-abrasive particles, with

the liquid being activated at ultrasonic frequency by a transducer installed through a wall of the tank, and with frequency and amplitude adjusted to achieve the desired result.

P108. Bodine, A. G., "Method of and Apparatus for Cutting Materials." U.S. Patent 2,460,919, Feb. 8, 1949 (filed Dec. 12, 1942). Reissue 23,657, May 19, 1953 (filed Sept. 2, 1952).

Metal surfaces containing scratches, ridges, indentations, and the like may be polished to a high finish by positioning a high-frequency vibratory source adjacent to the object to be treated, positioning a body of fluid containing cutting elements (such as abrasive particles) in the gap between the vibratory source and the object, and rapidly oscillating the cutting elements in the fluid. Frequencies of 1000 to 50,000 Hz were found suitable. Multiple parts may be processed at the same time.

P109. Hackett, J. C. and S. H. Johnson (Doehler-Jarvis Corp.), "Treatment of Articles to Remove Some of the Outside Material Therefrom or to Polish the Same." U.S. Patent 2,554,701, May 29, 1951 (filed March 4, 1947).

Polishing may be achieved by immersing an article (metal, ceramic, etc.) in a tank containing abrasive particles suspended in a liquid and introducing sonic or ultrasonic energy to induce relative particle motion between article and abrasive. Either the tank, the liquid, or the workpiece may be vibrated by any known method. The workpiece may be immersed in successive tanks containing progressively finer grit or in a single tank activated at variable frequencies. In production, a conveyor belt may be passed through the slurry. A higher quality finish is obtained in shorter time than by conventional methods.

P110. Martin, L. A. L. (La Soudure Electrique Languepin), "Process and Apparatuses for Cleaning and Surface Preparation of Materials, Chiefly Materials to be Joined by Electrical Resistance Welding." French Patent 1,087,439, Feb. 23, 1955 (filed July 31, 1953).

The surfaces of light metals or alloys to be welded are cleaned and polished by using a vibrating unit, the contacting surface of which is covered with a thin coating of the material being polished. The apparatus consists of a magnetostrictive transducer with excitation coil and a coupler attached thereto, which contacts the workpiece surface under pressure; the vibration thus induced disrupts oxide and other coatings and removes small protrusions from the surfaces, with or without heat application. The operation is performed immediately prior to welding.

Finishing

P111. Bodine, A. G., "Method and Apparatus for Sonic Polishing and Grinding." U.S. Patent 2,796,702, June 25, 1957 (filed Feb. 24, 1955).

This patent claims a method of polishing articles which comprises immersing the workpieces in a semi-fluid lubricant material containing fine abrasive particles, usually a mixture of oil, abrasive particles and iron particles, and rigidifying the fluid by an electromagnetic field while introducing vibratory energy through the tank walls or through the workpiece support. Alternately, the fluid may consist of abrasive particles in a starch solution which can be rigidified by an electrostatic field. The surface finish obtained is superior to that obtained with a liquid suspension (U.S. Patent 2,460,918--P107).

P112. Murdoch, A. (Telephonics Corp.), "Sonic Energy Apparatus." U.S. Patent 2,854,012, Sept. 30, 1958 (filed Jan. 15, 1954).

The apparatus comprises a cylindrical tank beneath which are mounted at least four magnetostrictive transducers which activate a liquid such as acid solution in the tank, effectively used not only for cleaning but also for pickling and etching of metal objects placed on racks in the tank. A peripheral liquid outlet causes a swirling action in the liquid so that accumulated debris is swept toward the center of the tank and is removed by operation of a valve. Etching and pickling are accomplished without embrittlement of the metal, since cavitation removes nascent hydrogen from the solution.

P113. Kline, J. E. (Micromatic Hone Corp.), "Resonant Honing." U.S. Patent 2,939,250, June 7, 1960 (filed Jan. 31, 1957).

Rapid and continuous honing and polishing of metal surfaces is accomplished by inducing in the workpiece surface or the tool a resonant-frequency vibration to produce a "self-dressing" effect on the abrasive tool. A magnetostrictive metal drive shaft may be used to rotate and reciprocate the honing body, or the transducer may be installed in the bed of the machine to vibrate the work table. The vibrations may occur parallel to the workpiece surface or lateral to the tool reciprocating motion. The process is said to prevent honing-stone glazing and reduce power and pressure requirements.

P114. Greening, J. H. (Micromatic Hone Corp.), "High Frequency Honing." U.S. Patent 2,939,251, June 7, 1960 (filed Feb. 18, 1957).

The proposed honing tool provides for the introduction of high-frequency vibratory energy when required only when the points of the grit particles become dulled and before any substantial glazing occurs to the working face. The transducer may be energized by a pressure switch that responds to change in pressure on the feed mechanism. Alternatively the transducer may be energized during the entire honing operation except at the end, when it is de-energized and the tool continued for a few strokes to provide the desired finish.

Finishing

P115. Brevik, E. L. (Purex Corp., Ltd.), "Equipment and Process for Deburring and Burnishing Metal Parts." U.S. Patent 2,994,165, Aug. 1, 1961 (filed Feb. 6, 1959).

The time required for deburring and polishing metal objects in a tumbling barrel with the aid of an abrasive slurry may be reduced as much as 70 percent when ultrasonic energy is applied to the tumbling media via generators installed within the barrel, and improved metallic luster is obtained.

P116. Balamuth, L. and A. Kuris (Cavitron Ultrasonics Inc.), "Ultrasonic Lapping Machines." U.S. Patent 3,093,937, June 18, 1963 (filed Nov. 30, 1962).

A lapping plate in the form of a torsional ring is vibrated radially at ultrasonic frequency with an amplitude that is uniform about the circumference of the plate. The workpieces are moved in orbital paths against the annular surface of the ring while abrasive slurry is applied therebetween to polish the workpieces. The annular surface may be provided with grooves. A high rate of stock removal is obtained while minimizing wear of the lap plate and frictional heating of the workpieces.

P117. Balamuth, L. (Cavitron Ultrasonics Inc.), "Method of Ultrasonic Removal of Material by Fatigue Failure." U.S. Patent 3,145,450, Aug. 25, 1964 (filed May 23, 1962).

A vibrating tool is used to remove burrs from machined edges or slag from the surface of a weld, because such burrs and slag have little fatigue resistance in comparison with the body from which they are removed. The tool is held against the work to create hammering action at the end or reciprocating friction along the side. No supplementary abrasive is required. Frequencies between 1 and 100 kHz may be used.

P118. Strom, B. and N. Radtke (SKF Industries, Inc.), "Honing Method." U.S. Patent 3,423,887, Jan. 28, 1969 (filed Jan. 14, 1966).

The surface of a body constituting a figure of revolution (such as an annular groove for ball bearings) may be honed by spinning the body about its axis while contacting it with an abrasive stone excited to vibration in range of 5-30 kHz. Preferably a liquid is applied to the surface so that cavitation occurs to prevent loading of the stone. This provides a rapid honing method with minimized waviness and departures from circularity in the finished part.

P119. Shiro, B. P. (Branson Instruments, Inc.), "Method and Apparatus for Applying Ultrasonic Energy to a Workpiece." U.S. Patent 3,535,159, Oct. 20, 1970 (filed Dec. 7, 1967).

Finishing

An ultrasonic method and apparatus are proposed for accomplishing cleaning, deburring, polishing, finishing, and separating parts more rapidly, efficiently, and effectively than by prior methods. Pulses at the rate of 20-100 kHz are applied to a transducer and thereby transmitted to a liquid which may contain an abrasive. Burrs on workpieces located in the liquid are fatigued and broken away due to heat generation and embrittlement, without affecting the main body of the workpiece, but the deburring operation must be carefully timed to avoid damage.

Miscellaneous Metal Removal

P120. McKechnie, I. C. (Elox Corp. of Michigan), "High Frequency Vibration." U.S. Patent 2,903,556, Sept. 8, 1959 (filed May 17, 1955).

Arc-machining or electrical discharge machining is accomplished with high-frequency (above 15 kHz) vibration of the electrode in order to eliminate "stringers" of eroded material, which normally accumulate in the gap between electrode and workpiece, and to promote flow of coolant through the gap. The operation is accelerated and improved surface finish is obtained.

P121. Isaev, A. I. and V. S. Anokhin, "Scraper." USSR Patent 140,304, filed Jan. 23, 1961.

To permit mechanical intensification of scraping, it is proposed to use a device consisting of a magnetostrictive transducer, one end of which is attached to a tapered coupler. At the small end of the coupler is the cutting blade which is excited to vibration in the axial direction and in the direction of the cutting motion. Automatic tuning is incorporated in the circuit to keep the ultrasonic system in resonance, since the resonant frequency of the blade changes with cutting action.

P122. Isaev, A. I. and V. S. Anokhin, "A Device for Transforming Acoustic Longitudinal Vibrations into Torsional." USSR Patent 148,971, filed Oct. 28, 1961.

For reaming and tapping, it is proposed to use an axially aligned device that transforms longitudinal into torsional vibrations. The device consists of a magnetostrictive transducer attached to a tapered coupler containing, at its opposite end, a conical hole for insertion of the cutting tool. At the middle portion of the rod-shaped cutting tool begins a spiral groove gradually deepening toward the end and executed with constant pitch, which provides the transformation of longitudinal to torsional vibration; the frequency depends on the length of the cutting tool plus the end portion of the coupler.

P123. McKechnie, I. C. (Elox Corp. of Michigan), "High Frequency Electrode Vibration." U.S. Patent 3,072,777, Jan. 8, 1963 (filed March 25, 1960).

An improved method for electrospark machining (cf. U.S. Patent 2,903,556--P120) provides for high-frequency vibration of the machining electrode at amplitudes sufficiently small to avoid actual contact between electrode and workpiece, even at minute gap spacing. The method employs a piezoelectric disk operating at a frequency of 15 to 60 kHz or higher to activate the electrode at controlled amplitude of vibration.

P124. Shaw, M. C., P. A. Smith, and N. B. Cook (LaSalle Steel Co.), "Method of Removing Metal by Shaving." U.S. Patent 3,157,093, Nov. 17, 1964 (filed Oct. 22, 1957).

In metal shaving, the shaving tool is vibrated axially to the work during advancement of the work through the shaving tool, in order to minimize material buildup on the tool edge. The tool may be mounted on a vibratory support or a support capable of being vibrated in the axial direction.

P125. Zhivitskii, A. S. and D. F. Iakhimovich, "Apparatus for Ultrasonic Cutting." USSR Patent 173,593, July 21, 1965 (filed April 14, 1964).

The patent is concerned with a heavy-duty saw with an ultrasonically activated blade, which is claimed to provide increased cutting rates with minimum deformation of the workpiece.

P126. Inoue, K., "Electrolytic Machining Apparatus Having Vibratable Electrode." U.S. Patent 3,252,881, May 24, 1966 (filed Feb. 4, 1964; priority in Japan Feb. 5, 1963).

The electrochemical machining of conductive workpieces is normally characterized by non-uniform current-density distribution across the gap separating the electrode from the workpiece surface, apparently resulting from ionic contamination and/or magnetic effects. Such effects are claimed to be substantially reduced by mechanically oscillating the electrode at a frequency of 10 to 10,000 Hz or by vibrating the electrolyte at 10 to 10,000 Hz, simultaneously with the passage through the electrolyte of a stream of pressurized gas to provide more homogeneous electrolyte flow.

P127. Weinberg, H. P. (Value Engineering Co.), "Etching Metals Rapidly and Uniformly While Ultrasonically Vibrated." U.S. Patent 3,411,999, Nov. 19, 1968 (filed Dec. 10, 1965).

Metal removal by chemical and electrochemical etching of refractory metals and alloys is accomplished by surrounding the workpiece with ultrasonic

vibrations uniformly distributed in the liquid through a water coupling separated from the etchant or electrolyte by a diaphragm. Etching is thus accomplished without deleterious effects such as uneven attack, and with substantially increased rate of attack. Examples are given of use of the process with aluminum, titanium, beryllium, and tungsten, and also of beryllium wire either bare or coated with nickel.

P128. Wiedenmann, "Ultrasonic Cutting," German Patent 2,057,080, May 31, 1972 (filed Nov. 20, 1970).

Filament coils and wire of tungsten and molybdenum may be cut by placing them in a groove of a grooved wheel anvil and contacting with a cutting edge excited to vertical ultrasonic vibration.

D. METAL JOINING

Solid-State Welding

P129. Martin, L. A. L. (La Soudure Electrique Languepin), "Process and Apparatus for Cold Joining of Materials." French Patent 1,087,440, Feb. 23, 1955 (filed July 31, 1953).

Materials such as light metals and alloys are joined without heat and without intermediate material by the introduction of high-frequency vibration into the workpieces held under consistent contact pressure. Precleaning of the workpieces is not necessary. The apparatus consists of a transducer which introduces vibration through a lateral coupler to a rod supported in a retaining ring. Load is applied through the rod via a spring or hydraulic or pneumatic cylinder. It is stated that a spot weld can be produced in less than 1/50 second.

P130. Makarov, L. O., "Process for Ultrasonic Welding and Apparatus for Carrying Out the Process." USSR Patent 132,060, filed Oct. 7, 1959.

A process and apparatus for ultrasonic welding are described wherein combined longitudinal-shear vibrations are introduced to the workpieces at an angle of less than 180° to the radiator. Various means are provided for supporting the workpieces, for welding two sets of workpieces simultaneously, and for accomplishing seam welding by alternate methods.

P131. Jones, J. B., W. C. Elmore, and C. F. DePrisco (Aeroprojects Inc.), "Method and Apparatus Employing Vibratory Energy for Bonding Metals." U.S. Patent 2,946,119, July 26, 1960 (filed April 23, 1956).

Ultrasonic spot welding is broadly covered by this process and apparatus patent. The metal parts to be welded are clamped together by two jaws of the apparatus, while one of the jaws is vibrated in a direction perpendicular to the clamping force, i.e., parallel to the weld interface plane. Electrical power to the transducer may range from 75 to 5000 watts, weld time from 1 msec to 6 sec, and frequency from 59 Hz to 300 kHz. Both similar and dissimilar metals can be joined in thicknesses from below 0.005 in. to 0.100 in. Welding may be initiated at room or elevated temperature. Clamping force is below the amount required to produce 10% deformation of the workpieces. The patent covers various types of apparatus designs.

P132. Jones, J. B., W. C. Elmore, and C. F. DePrisco (Aeroprojects Inc.), "Seam Vibratory Welding Apparatus and Method." U.S. Patent 2,946,120, July 26, 1960 (filed May 4, 1959).

Ultrasonic seam welding is accomplished with an ultrasonically activated rotating disk which engages the workpieces with force applied in a direction

perpendicular to the weld interface, with the vibratory energy acting parallel to the weld interface, and with the temperature in the weld zone below the melting point of the metals being joined. The supporting member for the workpieces may be a roller rotating in a direction counter to that of the welding disk or it may be a traversing table so that the peripheral speed of the disk is approximately equal to the translational speed of the supporting member. Various embodiments, which utilize a lateral-drive ultrasonic system, are described and illustrated.

P133. Apanasenko, V. P., "Ultrasonic Welding." USSR Patent 147,901, filed Dec. 28, 1960.

Ultrasonic welding of thick metals is accomplished with intermittent dephased focused vibrations which permit increased efficiency of ultrasonic transmission. The apparatus consists of a transducer soldered to a shaped amplitude transformer, to the free end of which is attached a reciprocating wave guide. Static pressure applied through the wave guide presses the workpieces against a table. The total energy utilized is the sum of the oscillation energy in the workpiece and the energy lost through reflection, heat dissipation, etc.

P134. Evtifeev, P. I., "Gripping Device for Ultrasonic Welding of Metals." USSR Patent 147,899, filed Jan. 9, 1961.

Patent describes a device which is capable of holding thin metals together for ultrasonic welding, with the potential for producing two continuous welds in different sets of workpieces simultaneously.

P135. Jones, J. B., C. F. DePrisco, and W. C. Elmore (U.S. Atomic Energy Commission), "Method and Apparatus Employing Vibratory Energy for Bonding Metals." U.S. Patent 2,985,954, May 30, 1961 (filed Sept. 5, 1956).

In ultrasonically welding metal members in a form difficult to hold in position by friction, welding is more easily accomplished if the vibratory energy is introduced through a sonotrode tip that mates with and positively engages one of the weldment members. This technique is useful for welding a wire or a member with converging sides to a surface.

P136. Scarpa, T. J. (Gulton Industries, Inc.), "Ultrasonic Control Circuit." U.S. Patent 2,995,689, Aug. 8, 1961 (filed Oct. 13, 1958).

The circuit for an ultrasonic system, particularly an ultrasonic welding system, incorporates automatic frequency control, whereby the driving frequency is continually adjusted to match the transducer frequency, which may

vary under load. This is accomplished with a feedback circuit coupled to a sweep signal which causes the generator to periodically scan a restricted range of frequencies. An amplitude modulator amplifies the signal at the resonant frequency. The circuitry can be effectively used when two or more transducers are driven by the same generator.

P137. DePrisco, C. F. (Sonobond Corp.), "Method and Apparatus for Bonding Metals." U.S. Patent 3,002,270, Oct. 3, 1961 (filed April 3, 1957).

Ultrasonic welds of improved strength between metals may be achieved by varying the frequency within a range of 10 to 1000 hertz around the center frequency at which welding is being effected. Such frequency wobble eliminates the difficulty of precise resonance adjustment for each workpiece. The wobbling may be accomplished by conventional mechanical or electronic means.

P138. Réalisations Ultrasoniques, "Improvements in Ultrasonic Welding Machines." French Patent 1,285,323, Jan. 15, 1962 (filed Jan. 3, 1961).

An ultrasonic continuous-seam roller welding device is proposed in which the rotating coupler-disk of previous machines is replaced by an assembly consisting of an elongated cylinder hollowed out along a portion of its length, with the diameter of the cavity increasing toward its open end, and an electrode comprising a ring of small width attached to this open end. The location of the ring constitutes an antinode of the vibratory amplitude transmitted along the cylinder. This design is said to permit achievement of maximum vibratory amplitude in the weld zone.

P139. Elmore, W. C. and C. F. DePrisco (Aeroprojects Inc.), "Vibratory Device." U.S. Patent 3,017,792, Jan. 23, 1962 (filed July 8, 1958).

This patent concerns a resonant disk tip for an ultrasonic roller seam welder in which the disk is designed to vibrate in its normal mode as a center-driven disk, with the energy being delivered to the periphery which contacts the workpiece. The disk diameter is large in comparison to the coupler attachment at the center, providing improved clearance behind the tip, reducing the number of revolutions required to weld a given seam length, eliminating tip bounce, providing greater contact between tip and weldment, and minimizing erosion or wear on the tip.

P140. Evtifeev, P. I., "Apparatus for Ultrasonic Seam Welding." USSR Patent 158,482, filed Jan. 24, 1962.

The apparatus described consists of ultrasonically excited wheels above and below the seam. Wheels are driven by counter-rotating drive wheels above and below the ultrasonically activated wheels.

P141. Réalisations Ultrasoniques, "Ultrasonic Welding Device." French Patent 1,286,759, Jan. 29, 1962 (filed Jan. 20, 1961).

An ultrasonic welding device incorporates a special member for clamping the parts to be welded and holding them in position, completely freeing the welding electrode from this function and permitting optimum adjustment of welding pressure. The pressure plate may have the shape of a doe's foot to permit passage of the electrode; it may be supplied with elastic supports or with rollers or with a pivot to permit rotation about an axis parallel to the weld interface. The pressure plate is hydraulically actuated.

P142. Gros, C. and J. Caperan (Société Helicotube), "Ultrasonic Welding Process." French Patent 1,295,980, May 7, 1962 (filed April 27, 1961).

A welding process for tube fabrication, in which a flat sheet is wrapped around a cylinder and the abutting edges are welded, consists of using electrical heating to preheat the edges to a temperature below the melting temperature of the metal, followed by ultrasonic roller seam welding in which one edge of the strip is excited to vibration with respect to the other edge. This obviates the necessity for very precise adjustment of electrical current before inducing fusion of the metal edges in the forging zone between the rollers; the preheating current can vary within a large enough range that its adjustment does not present a problem.

P143. Caperan, J. and F. Mayer (Société Helicotube et Laboratoire d'Electronique et d'Automatique Dauphinois), "Improvement in Ultrasonic Welding Machines." French Patent 1,298,433, June 4, 1962 (filed May 31, 1961).

In an ultrasonic continuous-seam roller welder, the supports for the upper roller are subjected to vibrations said to be harmful to their life; furthermore, rotation of the entire transducer-coupling system requires a turning support capable of resisting reaction forces and vibrations. According to the invention, the activated roller is replaced by a fixed vibrating member and the anvil support is a roller. It is stated that friction of the fixed tip on the workpiece is not increased because of the ultrasonic vibrations and presents practically no impediment to passage of the workpiece.

P144. Jones, J. B. and E. E. Weismantel (Aeroprojects Inc.), "Vibratory Device." U.S. Patent 3,038,359, June 12, 1962 (filed June 3, 1958).

An ultrasonic welding device that drives the tool in flexure consists of one or more couplers attached to a central reed wherein the reed has an integral flange to which the couplers are attached by welding, brazing, or soldering. Such construction provides a device with long useful life and is capable of transmitting high power without excessive fatigue failure.

P145. Jones, J. B., C. F. DePrisco, and E. E. Weismantel (Aeroprojects Inc.), "Apparatus for Introducing High Levels of Vibratory Energy to a Work Area." U.S. Patent 3,039,333, June 19, 1962 (filed June 3, 1958).

For ultrasonically welding relatively thick pieces of metal, more power is required than is available from a single transducer. For this purpose, two identical transducers operating at the same frequency are used to drive the reed member through a double bow-shaped coupler metallurgically attached to the respective ends of the coupler. Vibration of the transducers 180° out of phase provides increase in power delivery and lateral amplitude of the welding tip.

P146. Kholopov, Y. V. and A. S. Smirnov, "Apparatus for Ultrasonic Seam Welding." USSR Patent 159,097, filed July 20, 1962.

The patent describes an ultrasonically activated workpiece holder in the form of a hollow tube whose cross section corresponds to the outline of the weld. The patent claims that the device simplifies the technology involved while increasing productivity.

P147. Elmore, W. C. and C. F. DePrisco (Aeroprojects Inc.), "Vibratory Device." U.S. Patent 3,054,309, Sept. 18, 1962 (filed Feb. 20, 1959).

An ultrasonic welding coupler is provided with a free-free tip (free at both ends) perpendicular to and attached to the coupler at its center, the tip being resonant at the operating frequency of the welder. The tip is capable of delivering vibratory energy to a weldment through at least one of its end tip surfaces. Two such tips may be disposed on opposite sides of the materials being welded and operated 180° out of phase with each other. Such an arrangement provides substantial clearance behind the tip(s) for the workpieces.

P148. Jones, J. B. (Sonobond Corp.), "Vibratory Welding Process and Apparatus." U.S. Patent 3,056,192, Oct. 2, 1962 (filed Dec. 30, 1957).

In ultrasonic welding, the quality of the weldments may be monitored and maintained at optimum level by incorporating in the weldment support member a means for signaling the intensity of vibratory energy transmitted through the weldment members. One or more microphones resonant at a frequency other than the operating frequency embedded in the support member indicate when the energy

drops below a predetermined level. The energy level was shown to accurately reflect the tensile-shear strength of the weldment.

P149. Jones, J. B. and W. C. Potthoff (Sonobond Corp.), "Sandwich Construction Incorporating Discrete Metal Core Elements and Method of Fabrication Thereof." U.S. Patent 3,071,216, Jan. 1, 1963 (filed Dec. 29, 1958).

The invention concerns a light-weight sandwich construction with stand-off skin having high structural integrity and adaptable to compound curved structures, wherein two skins are separated by hollow spacer elements ultrasonically torsionally welded to both skins. The spacer elements have a frustroconical shape with an annular flange. This type of structure requires no great precision and is relatively simple to fabricate.

P150. Balamuth, L. and A. Kuris (Cavitron Ultrasonics, Inc.), "Ultrasonic Seam Welding Apparatus." U.S. Patent 3,088,343, May 7, 1963 (filed April 28, 1961).

In prior ultrasonic seam welding devices, the workpieces to be welded were clamped between a rotating sonotrode tip and a backup roller. This patent covers a seam welder in which the workpieces are clamped under pressure between a stationary tip and one or more movable backup members, while the tip is vibrated in a plane perpendicular to the axis of pressure application. The workpieces are drawn between tip and backup member with minimum frictional resistance, since the vibration reduces contact friction.

P151. Réalisations Ultrasoniques, "Electrode Holder Device for Ultrasonic Welding." French Patent 1,330,934, May 20, 1963 (filed May 19, 1962).

The proposed electrode holder for ultrasonic welding consists of at least two ultrasonic transmission members between the transducer and the electrode, so that the effectiveness of the coupler can be greatly increased without imposing undue strain on this member. One illustrated embodiment depicts a roller seam welding device in which the workpieces are clamped between two ultrasonically active rollers with truncated couplers oriented in opposite directions. A wedge-reed spot welding device can have one or more couplers disposed on opposite sides of the reed, with the attachments located at vibratory antinodes. Slots may be cut in the large bases of these conical members to prevent transverse vibrations.

P152. Dunbar, J. A. and S. G. Von Stocker (Aluminum Co. of America), "Splicing Aluminum Foil." U.S. Patent 3,100,337, Aug. 13, 1963 (filed July 12, 1960).

A method is provided for ultrasonically weld-splicing ends of aluminum foil webs in pack relationship consisting of two superimposed webs. The ends of the first web are ultrasonically spliced, a strip of stop-off material (such as paper, metal sheet, or flexible material) is placed over the first spliced web, and the second web is ultrasonically spliced. Because of the stop-off material, which is subsequently removed, no weld is effected between the first web and the second web.

P153. Cooper, J. B. (Gulton Industries, Inc.), "Sonic Welder." U.S. Patent 3,101,634, Aug. 27, 1963 (filed Sept. 12, 1960).

The ultrasonic welder consists of a transducer attached to a tapered coupler and vibrating in a compressional mode, a reflecting element attached to the small end of the coupler and inclined with respect to the longitudinal axis of this coupler, and a second tapered coupler attached to the reflecting surface at an angle of 45° to 120° with respect to the longitudinal axis of the first coupler. The reflecting surface converts the compressional vibration in the first coupler into transverse vibration in the second coupler, to which the welding tip is attached. Vibration is thus delivered to the weldment in the transverse mode.

P154. Jones, J. B. and N. Maropis (Sonobond Corp.), "Support for Workpiece to Be Subjected to Vibratory Energy." U.S. Patent 3,106,856, Oct. 15, 1963 (filed Jan. 16, 1961).

In ultrasonic welding, in order to prevent vibratory compliance of the anvil support at the operating frequency, the anvil is designed as a non-compliant member, so attached to a frame that it is vibratorily isolated from the frame and so that it may be angularly adjusted with respect to the frame.

P155. Carlin, B. (Branson Instruments, Inc.), "Ultrasonic Transducers." U.S. Patent 3,117,768, Jan. 14, 1964 (filed Nov. 21, 1960).

A transducer of high power and efficiency for such applications as ultrasonic welding consists of a composite stack of barium titanate elements each having its own pair of electrodes so that they can be individually activated to provide a combined vibratory action of increased power output. When the transducer is activated, each set of blocks may be alternately passive and active, and insulation may be provided between the blocks.

P156. Kampf, B., E. Kampf, and H. Kampf (Erwin Kampf Maschinenfabrik), "Apparatus for Winding into a Reel a Web of Material." British Patent 947,833, Jan. 29, 1964 (filed June 18, 1962; priority in Germany June 20, 1961).

A machine for splicing rolls of aluminum, copper, or thermoplastic foil incorporates an ultrasonic welding head with a roller-shaped sonotrode that is traversible along an anvil rail or bar to join torn ends of the web. The welding head can be swiveled between two anvil rails to join a web in either location.

P157. Scarpa, T. J. and V. P. Farley (Gulton Industries, Inc.), "Device for Welding Metal Foils and the Like." U.S. Patent 3,121,353, Feb. 18, 1964 (filed Feb. 8, 1962).

An ultrasonic seam welding device is proposed utilizing a thin blade-type tool attached at an angle of from 90° to 120° to the axis of the mechanical transformer. Longitudinal vibrations in the transformer are converted to transverse vibrations in the tool so that they apply shear vibration to the weldment. The welder is placed in contact with metal foils to be joined and is moved along the desired seam; or the welder may be fixed and the metal foils are moved with respect to the tool.

P158. Padgett, E. V. and D. H. Warf (U. S. Atomic Energy Commission), "Bonding Method." U.S. Patent 3,130,491, April 28, 1964 (filed July 26, 1962).

In ultrasonic welding of aluminum to itself, friction between the sonotrode and the workpiece is reduced by coating the workpiece in the weld area with a soap solution, such as a 1.5 to 4% aqueous solution of sodium or potassium stearate. This treatment eliminates the necessity for pre-weld cleaning, produces uniform bonds of high strength, and reduces bonding time.

P159. Jones, J. B. (Sonobond Corp.), "Positioning and Splicing Apparatus for Positioning and Splicing Webs." U.S. Patent 3,132,544, May 12, 1964 (filed March 25, 1959).

An apparatus is provided for positioning and splicing webs of metal foil, such as aluminum foil in the thickness range of 0.00017 to 0.006 inch, in which the unsatisfactory joining by resistance welding and the complications of adhesive joining are avoided, by joining separated ends of a foil roll by ultrasonic seam welding. The apparatus incorporates means for positioning and aligning the foil ends, and means for rotating an ultrasonic roller seam welding head across the overlapped ends superimposed on a support roller.

P160. Worlton, D. C. and R. A. Walker (U.S. Atomic Energy Commission), "Method and Device for Controlling Ultrasonic Welding Apparatus." U.S. Patent 3,153,850, Oct. 27, 1964 (filed July 18, 1962).

An ultrasonic welding device incorporates an electrophonograph pickup applied to the welding tip to sense its amplitude of vibration. As soon as the amplitude drops below a predetermined limit, indicating that a weld has been achieved, the power to the welder is automatically shut off.

P161. DePrisco, C. F. and W. M. Barfield (Aeroprojects Inc.), "Method and Means for Operating a Generating Means Coupled Through a Transducer to a Vibratory Energy Work Performing Device." U.S. Patent 3,158,928, Dec. 1, 1964 (filed March 30, 1962).

In operating an ultrasonic transducer-coupling system as in a welder, temperature changes in the system may result in frequency variations which alter its operating effectiveness. To eliminate this problem, a thermal sensing element whose resistance varies with temperature is incorporated and coupled to an electronic circuit which adjusts the frequency of the generating source to match the altered frequency of the transducer-coupling system.

P162. Bancroft, D., W. C. Elmore, J. B. Jones, and N. Maropis (Aeroprojects Inc.), "Apparatus and Method for Introducing High Levels of Vibratory Energy into a Work Area." U.S. Patent 3,166,840, Jan. 26, 1965 (filed June 28, 1961).

In an ultrasonic welding system, a plurality of flexible ribbons is used to transmit vibratory energy to the welding sonotrode. Such ribbons may be spaced around the periphery of the sonotrode, for example, to provide torsional or flexural vibration of the sonotrode. The ribbons may be driven by two or more transducers operating out of phase with respect to each other. Mention is made that such an arrangement can also be used for activating an extrusion die.

P163. Kholopov, Iu. V. and A. S. Smirnov, "Portable Apparatus for Two-Sided Spot Welding of Metals." USSR Patent 169,987, March 17, 1965 (filed April 10, 1963).

The device described in this patent is a hand-held ultrasonic welder with a pliers-type configuration. Requisite clamping force is achieved by pressing the handles together, and a force gauge is incorporated into the upper handle. Both upper and lower tips are ultrasonically activated.

P164. Jones, J. B. and C. F. DePrisco (Sonobond Corp.), "Method and Apparatus Employing Vibratory Energy for Bonding Metals." U.S. Patent 3,184,841, May 25, 1965 (filed June 3, 1958).

Process and apparatus are described for producing torsional or ring-type welds in which a complete circumferential weld (or a discontinuous circular

weld) is produced by torsional vibration of an annular welding tip. The apparatus consists of a torsionally resonant rod to which are tangentially affixed two (or more) transducer-couplers vibrating 180° out of phase, causing the rod and the welding tip attached thereto to vibrate in torsion.

P165. Maropis, N. (Aeroprojects Inc.), "Method and Apparatus for Delivering Vibratory Energy." U.S. Patent 3,184,842, May 25, 1965 (filed Aug. 3, 1961).

An ultrasonic welding device may be provided with a toroidal member which is forced to vibrate in torsion by introducing linear vibratory energy to the inner periphery of the toroid at its resonant frequency; the vibratory amplitude is amplified as it is transmitted to the outer periphery of the toroid. The device is effectively used for the production of continuous-seam or intermittent-seam weldments.

P166. Arnold, P. (Meaker Co.), "Ultrasonic Metal Foil Splicer." U.S. Patent 3,193,169, July 6, 1965 (filed Aug. 18, 1961).

An ultrasonic welding machine for joining the tail end of one metal strip to the beginning end of a second strip incorporates a carriage operating on a track adjacent to a guide roller for feeding the strip. The carriage contains a pivotally mounted ultrasonic welding means which rotates and moves across the overlapping foil ends, welding them together. A switch is disconnected when the carriage reaches a predetermined region at the end of the track.

P167. Knudsen, P. S. and E. Johansen (Strandhuse per Kolding), "A Method of Cold Welding with the Use of Ultrasonic Vibrations, and Apparatus to Carry the Method into Effect." British Patent 998,124, July 14, 1965 (filed April 16, 1962; priority in Denmark April 17, 1961).

An ultrasonic welding apparatus is described which is capable of producing a weld area substantially larger than a spot weld. The joint may be extended in length or width or several separate welded connections on an object may be made simultaneously. The sonotrode is designed to contact an object over the entire area to be welded.

P168. Jones, J. B. (Sonobond Corp.), "Process for Positioning and Splicing Webs." U.S. Patent 3,201,865, Aug. 24, 1965 (filed March 25, 1959).

A method and apparatus are provided for splicing metal foils and particularly for simultaneously splicing two separate webs of foil utilizing one or two ultrasonic seam welding devices which traverse the overlapped edges of the foil web, and trimming the free edges of the webs after welding is

completed. The apparatus includes a photoelectric means for detecting when the welding disk has reached the end of the foil.

P169. Jones, J. B. (Aeroprojects Inc.), "Transducer Coupling System." U.S. Patent 3,209,447, Oct. 5, 1965 (filed March 12, 1962).

A lateral-drive overhung-coupler ultrasonic welding system is provided wherein the coupler has a length equal to an integral number of half wavelengths, the welding tip is located at an integral number of half wavelengths from the free end, and force is applied to the coupler between the tip and the free end at an odd number of quarter wavelengths from the tip, in a direction perpendicular to the coupler axis. This arrangement eliminates bending softness and bounce in the coupler and provides an essentially force-insensitive array.

P170. Jones, J. B. (Sonobond Corp.), "Vibratory Welding Method and Apparatus." U.S. Patent 3,209,448, Oct. 5, 1965 (filed March 12, 1962).

Ultrasonic welds having an elongated weld area (line welds) with [illegible] bond quality over the entire length are produced with a single weld pul[illegible] an apparatus consisting of a plurality of lateral-drive, overhung couple[illegible] n an elongated welding tip extending transversely across the couplers at an an[illegible] node on each member and means for applying force uniformly or selectively al[illegible]g the entire length of the tip. Using such apparatus, an aluminum can body can be produced by wrapping thin aluminum sheet around an anvil and welding on the overlapped edges of the sheet with a single weld pulse.

P171. Jarvie, A. G. and G. E. Stimson (General Electric Co.), "Welding Apparatus." U.S. Patent 3,217,957, Nov. 16, 1965 (filed Dec. 12, 1958).

Ultrasonic [illegible]ntinuous seam welding equipment consists of a transducer, a coupler, and a rotatable disk designed to transmit vibrations to its periphery so that it vibrates in a plane transverse to the axis of the system. The ultrasonic unit is supported at a node on a movable carriage and rotates as the disk moves across the workpiece. Means are provided for applying a load to the carriage. A continuous weld is produced without excessive abrasion of the work or excessive thickness reduction.

P172. Wyczalek, F. A. (General Motors Corp.), "Sonic Vibration Spot Welder." U.S. Patent 3,225,997, Dec. 28, 1965 (filed July 31, 1962).

This vibratory welding device consists of a movable upper anvil through which clamping force is applied and a stationary resonant column to which the welding tip is affixed, the column being excited to vibration in the flexural or torsional mode by a fluid-driven vibrator consisting of a roller driven

eccentrically in a circular race utilizing compressed air. The offset position of the vibrator with respect to the column axis causes rotation of the column and transmits vibratory energy thereto. The device is reportedly capable of higher power levels than a magnetostrictive system.

P173. Zaitsev, M. P., Iu. V. Kholopov, and A. M. Mukhachev, "Instrument for Ultrasonic Welding of Metals." USSR Patent 181,966, April 21, 1966 (filed Oct. 5, 1964).

The patent describes a production machine which ultrasonically welds two sheets of metal together in two locations while cutting away the intervening section of the top layer of metal.

P174. Rykalin, N. N., Iu. I. Kitaigorodskii, M. G. Kogan, L. L. Silin, and V. A. Kuznetsov, "Method of Welding Metals." USSR Patent 182,488, May 25, 1966 (filed Jan. 13, 1958).

An ultrasonic welding apparatus is described which delivers transverse vibrations through a coupling member to the workpiece and includes a hydraulic mechanism for applying external clamping force. It is claimed that less than 1/4 wavelength of material overlap or overhang is required to produce quality welds.

P175. Rykalin, N. N., Iu. I. Kitaigorodskii, M. G. Kogan, L. L. Silin, and V. A. Kuznetsov, "Stability for Roller Welding Pressure with Ultrasonic Application." USSR Patent 182,489, May 25, 1966 (filed Jan. 13, 1958).

The patent describes an ultrasonic seam welding device which delivers vibrations to the workpiece in the transverse mode. The welder is suspended from an arm by three braces which act as force-insensitive mounts. Clamping force is applied from beneath the workpiece. Alternate devices for supporting the workpiece and creating relative motion between the welder and the workpiece are described.

P176. Wands, H. G. and S. L. Williams (Gustin-Bacon Manufacturing Co.), "Method for Adhering and Sealing Foil to Glass Fiber." U.S. Patent 3,256,122, June 14, 1966 (filed May 4, 1962).

A method is proposed for utilizing ultrasonic welding to seal heavy aluminum foil on the exterior surfaces of glass fiber ducts to provide a vapor barrier. The duct is installed on a mandrel, one edge of the metal foil is pinned thereto, the mandrel is rotated until a double thickness of foil is achieved, and an ultrasonic seam weld is produced on the overlap.

P177. Jones, J. B. (Aeroprojects Inc.), "Method and Apparatus for Employing Torsional Vibratory Energy." U.S. Patent 3,257,721, June 28, 1966 (filed March 16, 1965).

An improved ultrasonic torsional welding system, which provides an effective, inexpensive means for increasing the practicability, adaptability, and versatility of the ring-welding process, consists of a torsional reed terminating in a hollow tapered torsional transformer capable of increasing the vibratory amplitude. The transformer is interchangeably attached to the reed by meshed serrations. Vibratory energy is introduced into the reed through transducer-coupling systems attached tangentially to the reed at low stress areas.

P178. Pohlman, R. and R. Sievers (Dr. Lehfeldt and Co., GmbH), "Apparatus for Ultrasonic Welding." German Patent 1,220,235, June 30, 1966 (filed Jan. 25, 1962).

In an ultrasonic welding device, in order to improve coupling between the sonotrode and the workpieces, the sonotrode and anvil tips are roughened or provided with grooves, either circular or transverse to the direction of vibration.

P179. Varley, V. P. (Gulton Industries, Inc.), "Rotating Sonic Welder." U.S. Patent 3,292,838, Dec. 20, 1966 (filed Oct. 10, 1960).

An ultrasonic seam welder in which the tool tip rotates with respect to the work incorporates a variable-speed, reversible motor which provides rotational motion through a sprocket and chain, and chain and sprockets for moving the welding head linearly along the welding path for a fixed distance then reversing the direction of motion. The device is said to operately with uniformly smooth contact along the seam length.

P180. Jones, J. B. and C. F. DePrisco (Sonobond Corp.), "Welds." U.S. Patent 3,319,948, May 16, 1967 (filed Oct. 26, 1964).

An ultrasonic ring-type weld between juxtaposed metal members can comprise a true annulus or have at least one non-welded discontinuity. Such welds can be non-circular in plan form, for example, square, rectangular, elliptical, or a closed loop of any shape as long as the maximum to minimum radius is not more than about 5:1. In addition, spot welds of annular, square, or other shape may be produced by torsional welding equipment. Apparatus for producing such welds is described.

P181. Zaitsev, M. P. and J. V. Kholopov (Vsesojuzny Nauchno-Issledovatelsky Institut Electrosvarochnogo Oborudovania), "Ultrasonic Welder." British Patent 1,073,191, June 21, 1967 (filed May 11, 1964).

The welder comprises a magnetostrictive converter (transducer) attached to a connecting link (coupler) for transmitting vibrations to an active resonance rod (sonotrode) rigidly affixed to the welder body and serving as a support for the workpieces, and comprises also an opposing passive resonance rod (anvil) through which contact force is applied from above. (This represents an inversion of the standard wedge-reed welding arrangement.)

P182. Wyczalek, F. A. (General Motors Corp.), "Sonic Vibration Spot Welding." U.S. Patent 3,333,323, Aug. 1, 1967 (filed July 31, 1962).

This patent covers the method of vibratory welding utilizing the apparatus of U.S. Patent 3,225,997 (P172) and consists of clamping the weldment members between two columns, one of which is driven by a fluid-actuated vibrator in a combined torsional and oscillatory mode at the resonant frequency of the column and directs vibratory energy to the part in contact with the weldment members.

P183. Attwood, J. G. and R. L. Kosrow (Union Special Machine Co.), "Vibratory Apparatus." U.S. Patent 3,350,582, Oct. 31, 1967 (filed Jan. 13, 1965).

This patent concerns an ultrasonic tool such as a welding device in which the transducer is provided with a supporting structure separate from that of the tool itself. A wire mesh or electrically conductive adhesive is interposed between the transducer and its support to absorb vibrations of the transducer and provide a series of electrically conductive paths. Such adhesive is also located between transducer and tool to permit transmission of electrical and mechanical energy.

P184. Avila, A. J. (Western Electric Co.), "Vibratory Bonding Utilizing a Tuned Anvil." U.S. Patent 3,360,850, Jan. 2, 1968 (filed May 24, 1965).

Ultrasonic seam welding, for example for bonding a seam on a tubular member formed from flat strip stock, is accomplished with more efficient energy utilization and at higher welding rates with the use of an acoustically resonant anvil supported at one or more points. On the anvil is produced a standing-wave pattern having an antinode at the point of application of vibratory energy and a node at each anvil support point.

P185. Zaitsev, M. P. and J. V. Kholopov (Vsesojuzny-Nauchno-Issledovatelsky Institut Elektrosvarochnogo Oborudovania), "Ultrasonic Welder." U.S. Patent 3,375,965, April 2, 1968 (filed Oct. 27, 1964).

An ultrasonic spot-type welder is described wherein vibratory energy is transmitted horizontally to a vertical rod rigidly fixed at its lower end to a cantilever member and a second rod is vertically aligned above the first rod for clamping the workpieces between the adjacent ends, a drive being connected to the second rod for adjustment of its vertical position. The arrangement offers a simple design and reliable welder operation.

P186. Daniels, H. P. C. (North American Philips Co., Inc.), "Method and Device for Ultrasonic Welding." U.S. Patent 3,380,150, April 30, 1968 (filed July 31, 1967; priority in Netherlands Dec. 9, 1963).

An ultrasonic seam welding apparatus includes a vibrating member vibrated along a given axis and a movable support member located adjacent to the free end and to one side of the vibrating member. In the preferred embodiment, the support member includes a roller free to rotate about the axis of vibration so that the workpieces are simultaneously welded together and propelled in a direction parallel to the axis of vibration.

P187. Lehfeldt, W., F. Muegele, R. Sievers, and R. Pohlman (Dr. Lehfeldt and Co., GmbH), "Process for Producing an Ultrasonic Weld Assembly." German Patent 1,427,329, Jan. 16, 1969 (filed Sept. 29, 1962).

An ultrasonic line weld of extended length is produced by a bar excited to vibration by multiple transducers. The bar may be straight or curved, and either bar or anvil may be heated. Uniform pressure along the weld line may be achieved by anvil mounting on a universal joint or on elastically compliant members, or by pre-embossing the line to be welded. For thicker weldments, both the line tip and the anvil may be made to vibrate.

P188. Daniels, H. P. C. (N. V. Philips' Gloeilampenfabriken of Eindhoven), "Apparatus for Ultrasonic Welding." German Patent 1,287,420, Jan. 16, 1969 (filed March 2, 1964; priority in Netherlands March 6, 1963).

This patent concerns an apparatus for ultrasonic seam welding in which the anvil is a rotatable roller and the sonotrode is essentially perpendicular to the axis of the anvil. The ultrasonic energy from the sonotrode acts in conjunction with the clamping force to produce forward motion of the workpieces.

P189. Pohlman, R. and R. Sievers (Dr. Lehfeldt & Co., GmbH), "Ultrasonic Welding Apparatus." U.S. Patent 3,426,951, Feb. 11, 1969 (filed Oct. 31, 1962; priority in Germany Nov. 6, 1961).

An ultrasonic welding machine may be provided with welding tips and/or anvils having striated surfaces which substantially eliminate relative motion between tip or anvil and the weldment material. In other embodiments, the sonotrode material is non-alloying with the weldment material. In addition, the sonotrode is vibrated after welding in order to break contact.

P190. Maropis, N. and J. B. Jones (Sonobond Corp.), "Vibratory Welding Apparatus and Method." U.S. Patent 3,429,028, Feb. 25, 1969 (filed June 28, 1968).

Ultrasonic cylinder welding method and apparatus are provided wherein a cylinder may be welded to the inner periphery of another member. The welding tip is supported so that its longitudinal axis generates a cone with its apex at the support means while rotating the location of force application in a direction opposite to that of the rotating welding tip.

P191. Van Der Burgt, C. M. (North American Philips Co., Inc.), "Welding Apparatus Provided with a Vibrating Contact Tip." U.S. Patent 3,436,005, April 1, 1969 (filed Feb. 5, 1963; priority in Netherlands Feb. 13, 1962).

The ultrasonic welding apparatus incorporates a transducer coupled to horn sections disposed laterally, with clamping force on the weldment acting vertically from an upper mass through a support rod which freely contacts the small end of the amplitude transformer (horn) at right angles. The thickness of the rod is a fraction of the horn thickness at this point, and its length is dimensioned to be resonant at the operating frequency.

P192. Daniels, H. P. C. and F. M. A. Rademakers (U. S. Philips Corp.), "Ultrasonic Welding Method and Apparatus." U.S. Patent 3,455,015, July 15, 1969 (filed Dec. 16, 1965; priority in Netherlands Dec. 16, 1964).

An ultrasonic welding apparatus and method is described for bonding a foil of a ductile material such as aluminum to a thin layer of hard, brittle material such as tungsten or glass. Two parallel cylinders sandwich the foil and brittle specimen and are rotated, pulling the specimens between them. One cylinder is ultrasonically activated, and the other is covered with a thin layer of elastic material which prevents fracture of the brittle material during welding.

P193. Christensen, F. W. (Western Electric Co., Inc.), "Short Pulse Vibratory Bonding." U.S. Patent 3,458,921, Aug. 5, 1969 (filed July 19, 1965).

An optimum ultrasonic bond is formed by accurate control of the ultrasonic energy applied to the bond. With excess energy, bond degradation occurs, and with too little energy no bonding occurs. Damping facilities are employed to bring the bonding tip to rest at the end of the weld pulse and prevent continuing vibration.

P194. Hauser, R. L. (Branson Instruments, Inc.), "Method of Bonding Using Exothermic Adhesive Activated by Ultrasonic Energy." U.S. Patent 3,480,492, Nov. 25, 1969 (filed Feb. 20, 1967).

In a bonding process involving the use of an adhesive such as epoxy, improved bonding is obtained by applying ultrasonic energy to the bond and by adding to the adhesive an ingredient (such as potassium chlorate, perchlorates, nitrates, or peroxides) which undergoes exothermic reaction with ultrasonic activation, thereby providing a sudden increase in curing temperature and accelerating the curing cycle.

P195. Jugler, J. (Branson Instruments, Inc.), "Control Circuit for Tool Driven by Sonic Energy." U.S. Patent 3,493,457, Feb. 3, 1970 (filed Jan. 6, 1967).

This invention relates to a tool such as an ultrasonic welding tool which transfers vibratory energy to a workpiece and is brought into forced engagement with the workpiece. Control means, such as an electrical switch, are provided to ultrasonically activate the tool only in response to the reaction of the force applied between tool and workpiece. This arrangement overcomes problems of mechanical tolerances in the workpiece, eliminates difficult mechanical alignment and setting of limit switches, and eliminates operator judgment as to the precise point when ultrasonic energy is to be initiated.

P196. Williams, F. S. and R. L. Abbott (U. S. Secretary of the Navy), "Corrosion Inhibiting Process." U.S. Patent 3,528,165, Sept. 15, 1970 (filed April 24, 1967).

The invention concerns a means for minimizing corrosion about the heads of fasteners (bolts and nuts, etc.) on aircraft structures wherein at least one exterior surface of the structural member is recessed about the hole and a metallic patch is placed over the recessed surface to completely cover the fastener head and is ultrasonically welded thereto to provide a finished flush exterior surface.

P197. Obeda, E. G. (Branson Instruments, Inc.), "Solid Horn With Cooling Means." U.S. Patent 3,529,660, Sept. 22, 1970 (filed Nov. 20, 1968).

A solid horn used for sonic or ultrasonic processing such as welding is provided with gas cooling means which include a central longitudinal bore, a plurality of radial gas escape holes, and a shroud for directing the gas flow along the horn.

P198. Robinson, P. T. (Motorola, Inc.), "Method for Ultrasonically Welding Using a Varying Welding Force." U.S. Patent 3,610,506, Oct. 5, 1971 (filed June 11, 1969).

In ultrasonic welding of metals, improved weld quality is obtained by progressively increasing the welding force during the period of vibratory energy application. Thus a lighter welding force is desirable during the initial scrubbing phase of the welding cycle and heavier force at the end of the cycle when there is small or zero vibratory amplitude.

P199. Humpage, R. W. (Joseph Lucas Industries Ltd.), "Ultrasonic Welding Tools." U.S. Patent 3,612,385, Oct. 12, 1971 (filed March 10, 1969; priority in Great Britain, Dec. 15, 1966).

In an ultrasonic welder, the transducer-coupling system is supported against lateral movement relative to the frame by engaging an axially extending portion of the assembly, of uniform cross section, as an axial sliding fit in a bearing which is fixed relative to the frame.

P200. Miller, A. Z. (RCA Corp.), "Method of Bonding Metals Together." U.S. Patent 3,662,454, May 16, 1972 (filed March 18, 1970).

A soft metal, such as gold, silver, or copper, is ultrasonically welded to another metal by providing a thin layer of harder metal (nickel, iron, cobalt, etc.) between the two metals. The thin hard metal is worn away during application of ultrasonic energy in order to provide a bond directly between the soft metal and the other metal.

P201. Walraven, T., N. Maropis, W. C. Elmore, and J. Devine (Aeroprojects Inc.), "Contra-Resonant Anvil." U.S. Patent 3,695,500, Oct. 3, 1972 (filed June 1, 1970).

It has been established that improved ultrasonic welding performance can be achieved when the anvil vibrates out of phase with the welding tip, i.e., with a resonant frequency somewhat above or below the resonant frequency of the welding tip. The anvil is designed to be induced to vibration out of phase with the welding system.

Soldering and Coating

P202. Barwich, H., "Process and Apparatus for Soldering Objects of Aluminum, Etc." German Patent 702,629, filed May 27, 1938.

Metals such as aluminum, which have refractory oxide coatings, may be soldered or tinned with the aid of vibratory energy, preferably ultrasonic. The oxide film is ruptured so that the solder contacts the surface directly. Either the workpieces may be vibrated or they may be immersed in a molten bath which is vibrated. Several suggested arrangements are described and illustrated.

P203. Fides Gesellschaft für die Verwaltung und Verwertung von Gewerblichen Schutzrechten mit beschränkter Haftung, "Improvements in and Relating to the Production of Metal Coverings." British Patent Application 15,773, May 26, 1939.

Soldering and tinning of various metals and alloys with extremely strong adhesion of the solder to the base metals is achieved by setting up high-frequency vibrations in the part to be soldered in contact with the molten metal or in the molten solder bath. Various arrangements are described. The process is suitable for mass production.

P204. Schöfer, R. (Siemens-Schuckertwerke A.G.), "Apparatus for Coating, Particularly for Tinning the Ends of Wires." German Patent 706,593, April 30, 1941 (filed Nov. 25, 1939).

An apparatus for coating wire ends, particularly aluminum wire, comprises a rod-shaped magnetostrictive transducer located in the melt crucible and supported by a diaphragm located at a vibratory node. A central borehole in the rod contains molten solder admitted throuth small lateral openings; the wire ends are placed in the solder and the transducer is activated. An adherent coating is produced within a short time. The melt vessel may be surrounded by a heating coil.

P205. Green, C. G., "Improvements Relating to Metallizing, Soldering, Welding and Like Processes." British Patent 636,680, May 3, 1950 (filed Dec. 10, 1946).

In order to obtain soldered or welded joints of good adhesion and strength, particularly in light metals and alloys, a metallic or nonmetallic workpiece may be immersed in molten metal which is mechanically vibrated at a frequency in the range of 15-54 kHz, or the workpiece itself may be vibrated. Specific applications mentioned include tinning the ends of wires, wire joining, butt joining, and the like.

P206. Arnold, O. M., "Bonding Method." U.S. Patent 2,522,082, Sept. 12, 1950 (filed Feb. 3, 1945).

Objects may be coated with organic, molten metal, powder, sheet, or solid coatings by first subjecting the object to one or more frequencies in the anomalous dispersion range (where the molecular activity of foreign substances is greatest as determined by the dielectric curve) to drive off impurities, then applying the coating together with or followed by further vibratory treatment. Chemical reaction or molecular association between base metal and coating is thus achieved.

P207. Hartmann, L., "Metal Spraying Process." Austrian Patent 171,420, Nov. 15, 1951 (filed Oct. 14, 1946; priority in Germany April 24, 1944).

Metal spray coating under ultrasonic influence produces a strong bond and a non-porous homogeneous coating structure, for example with lead linings, coating light metals on steel or glass, copper-plating or gold-plating on ceramic materials, zinc-tinning of carbon, and the like. The ultrasonic energy may be applied to the metal bath which is to be sprayed, to the spraying device, to the melting flame or arc, to the spray issuing from the nozzle, or to the base material during the coating process.

P208. Muss, H. (Ultrakust Geratebau), "Production of Zinc Coatings." German Patent 827,281, Jan. 10, 1952.

Plating of metal surfaces with zinc coatings is accelerated and uniform zinc coatings are obtained when the molten zinc bath is subjected to ultrasonic vibrations during the plating operation.

P209. Hartmann, L., "Soldering Light Metals." Austrian Patent 173,927, Feb. 10, 1953.

Combinations of ordinarily immiscible metals, such as Al-Pb-Si or Cr-Bi or Co-Ag, may be used as solder if the solder and flux are irradiated with ultrasonic waves before they are brought in contact with the workpiece. The treatment preferably is carried out in the melting pot and under cover of a protective gas.

P210. Leemann, A. (Siemens-Schuckertwerke A.G.), "Apparatus for Producing Soldered or Welded Joints." German Patent 906,961, July 2, 1953 (filed April 6, 1943).

In soldering or welding under ultrasonic influence, the driving ultrasonic generator is provided with adjustment means such as frequency sweep to

widen the resonance peak of the frequency curve of the generator so that the operating circuit is always excited at its resonant frequency despite temperature-dependent changes in its natural frequency.

P211. Espe, W. (Siemens-Schuckertwerke A.G.), "Process for Coating Strip or Wire-Shaped Metal Materials with a Coating Metal." German Patent 895,085, Sept. 17, 1953 (filed June 18, 1943).

Strip or wire metal is continuously coated with a thin metal coating by drawing the strip or wire through a preliminary solder bath to preheat the material, then through a channel into the main bath where one or more ultrasonic couplers are located in close proximity to the path of the strip. The traverse speed is adjusted to provide the desired coating thickness without producing undesirable weakening of the base material.

P212. Maier, H. N. (National Lead Co.), "Apparatus for Impregnating and Coating Porous Bodies." U.S. Patent 2,657,668, Nov. 3, 1953 (filed June 4, 1948).

Impregnation or coating of a porous material, as with resin, oil, or paint, is accelerated by transmitting vibratory energy (sonic or ultrasonic) through the liquid in which the workpiece is immersed, preferably through a diaphragm in one wall of the tank. Dirt particles are thus removed from the workpiece and superior penetration and bonding are obtained. In some cases, extra operations are eliminated.

P213. Birkbeck, G., D. J. Tremmlett, B. E. Noltingk, and E. A. Neppiras (Hartford National Bank and Trust Co.), "Magnetostrictive Transducer." U.S. Patent 2,676,236, April 20, 1954 (filed March 23, 1951; priority in Great Britain March 31, 1950).

Soldering iron consists of a body of inverted channel section containing a pistol grip, a soldering bit projecting from one end of body and supported at midpoint by diaphragm, a laminated magnetostrictive transducer brazed to end of bit and supported at midpoint, an electromagnetic pickup on rear end of transducer with leads to a thermionic valve amplifier used to energize transducer windings and providing automatic frequency control. The bit is electrically heated, with a separate switch for heating so the iron may also be used for normal soldering without vibration.

P214. Maguire, C. R. and A. W. Cronshaw (Metropolitan-Vickers Electrical Co., Ltd.), "Improvements Relating to Ultrasonic Soldering Irons Suitable for Use in Tinning Aluminum and Its Alloys." British Patent 719,386, Dec. 1, 1954 (filed Aug. 22, 1951).

Soldering and Coating

An ultrasonic soldering iron tip may be provided with an aperture or open slot shaped to embrace the workpiece to be tinned. The workpiece is passed through the aperture in the presence of molten solder while the iron is activated at ultrasonic or high sonic frequency.

P215. Iglesias, L. R., "Electrical Ultrasonic Soldering Iron for Soldering Aluminum and Other Metals." Italian Patent 504,294, Dec. 10, 1954 (filed Aug. 27, 1953).

The soldering iron consists of a magnetostrictive transducer to which an interchangeable soldering tip is rigidly attached, a resistance heater enclosed in a cylinder of refractory material, an appropriate housing, and suitable electrical current. The iron is designed to operate as a normal soldering iron without ultrasonic activation if desired.

P216. Gerecke, W. (Junkers Flugzeug- und Motorenwerke A.G.), "Process for the Production of Compound Metal Workpieces." German Patent 932,336, Aug. 4, 1955 (filed Oct. 10, 1943).

A compound metal workpiece consisting of a base metal and a coating metallurgically bonded to it by weld plating or the like is achieved with uniformly good adhesion by vibrating one part with respect to the other during bonding. The frequency of vibration can extend from the infrasonic to the ultrasonic range and can be applied to one or both members. The process is especially useful with parts subjected to high-temperature service such as gasoline engine pistons or bearing boxes.

P217. Schmid, R. (Siemens & Halske A.G.), "Process for Partial Tinning of Metal Parts with Oxidized Surfaces, Particularly Aluminum Parts." German Patent 934,449, Sept. 22, 1955 (filed April 10, 1951).

When a workpiece is to be tinned in only incremental areas, the workpiece may be placed in a ultrasonically activated heated solder oil bath and the desired surface to be tinned is stroked with a soldering rod on the immersed surface to be tinned. The parts to be tinned may be heated by induction coils so that the solder in contact with the part remains fluid.

P218. Thiede, H. (Atlas-Werke A.G.), "Molten Tin Bath for Tinning of Aluminum Wire." German Patent 1,004,013, March 7, 1957 (filed April 6, 1954).

It is noted that improved adherence of a tin coating on metal can be achieved by tinning under ultrasonic influence, but even these coatings are subject to oxidation with extended storage, and embrittlement and chipping of the coating may occur. According to the invention, improved life of the tin coating may be obtained by adding a small percentage of beryllium metal to the solder.

Soldering and Coating

P219. Jones, J. B. (Aeroprojects Inc.), "Ultrasonic Soldering Iron." U.S. Patent 2,803,735, Aug. 20, 1957 (filed Oct. 6, 1955).

This patent describes a compact, efficient soldering iron comprising a magnetostrictive transducer attached via a coupler to a soldering tip surrounded by a tip heater. Transducer and coupler are enclosed in a housing spaced from the internal members to provide a passageway for air to cool transducer and coupler. Also included are a generator to supply current to the transducer and an air pressure control box.

P220. Ganrio, V. V. and B. P. Zeldin, "A Method for Tinning and Soldering Products of Ceramics, Abrasives, Ferrites and the Melting Points of the Materials." USSR Patent 116,865, filed Sept. 20, 1957.

In soldering and tinning various types of materials, rate increases and higher bond strength can be obtained by ultrasonic application. The proposed process consists of heating the workpiece, melting the solder and applying it to the workpiece, and immersing the ultrasonically activated tip in the molten solder and moving it around on the workpiece. Reliability and strength are obtained in 0.1-0.2 second. The workpiece may be heated in a furnace or by electrical means, or with a gas burner, and must achieve a temperature above the melting point of the solder.

P221. Weiss, M. E. (Gulton Industries, Inc.), "Ultrasonic Soldering Iron." U.S. Patent 2,815,430, Dec. 3, 1957 (filed Feb. 28, 1956).

This soldering iron, which may be used with either electrically heated or gas-heated tips, provides minimum heat transmission from tip to transducer. The heating element may be located inside a hollow tip and sealed with ceramic sealing material. The tip is attached to the small end of a velocity transformer which is made of a low-thermal-conductivity material, while its support (at a vibratory node) has high thermal conductivity to dissipate heat.

P222. Brown, G. G. (Bendix Aviation Corp.), "Ultrasonic Tinning Apparatus." U.S. Patent 2,824,543, Feb. 25, 1958 (filed Jan. 14, 1955).

This apparatus, which provides for greater tinning surface and greater energy than the usual ultrasonic soldering iron, includes an ultrasonically activated, shallow-top container for the molten solder. The object to be tinned is pressed or moved against this vibrating surface, which may be of copper or stainless steel because of their good thermal conductivity and low acoustical impedance.

P223. Carlin, B. (Alcar Instruments, Inc.), "Ultra-Sonic Magnetostriction Transducer Devices." U.S. Patent 2,830,165, April 8, 1958 (filed Dec. 21, 1955).

Soldering and Coating

These devices incorporate an adjustable clamp, in the form of a retaining ring with ball-bearing support, which can be shifted along the length of a magnetostrictive rod transducer to vary the frequency. If clamped at 1/4 overall length, its resonant frequency is equivalent to that of a rod half its length. The clamping device may be used on an ultrasonic soldering iron, soldering pot, or any other magnetostrictive transducer device.

P224. Jones, J. B. (Aeroprojects Inc.), "Ultrasonic Brazing Unit." U.S. Patent 2,833,238, May 6, 1958 (filed July 26, 1956).

Brazing, which uses a filler metal having a melting point in excess of 800°F, may be accomplished with ultrasonic activation of the brazing tool, producing a sound joint without the necessity for flux and eliminating the accelerated corrosion effected by the use of flux. The brazing unit consists of a transducer, preferably magnetostrictive, enclosed in a housing and coupled to a brazing tip surrounded by a gas heater, and means for flow of cooling gas through the housing.

P225. Jones, J. B. and W. C. Potthoff (Aeroprojects Inc.), "Method for Applying Metallic Coatings." U.S. Patent 2,895,845, July 21, 1959 (filed Dec. 7, 1955).

A method is provided for continuously coating a moving strip of metal having a relatively high melting point with a metal of lower melting point, wherein the high-melting metal is heated and the low-melting metal in molten state is coated thereon and is contacted with an ultrasonically activated tip which has sufficient vibratory energy to effect cavitation in the molten metal and bonding to the underlying metal. Thus steel may be coated with aluminum or solder alloy, or bearing core material coated with bearing metal without the use of flux.

P226. Carlin, B. (Alcar Instruments, Inc.), "Transducers Used in Ultrasonic Equipment." U.S. Patent 2,896,099, July 21, 1959 (filed April 4, 1955).

An ultrasonic soldering transducer comprises a magnetostrictive rod, one-half length of which is laminated and the other half solid. The solid part is surrounded by a coil in which the voltage drops with current flow, thus heating the rod to prevent solidification of the solder. This eliminates the necessity for a separate heater tip.

P227. Linden, H. E. (American Mollerizing Corp.), "Method and Means for Continuously Pretreating and Coating Vibrating Metal Objects." U.S. Patent 2,900,273, Aug. 18, 1959 (filed Sept. 26, 1955).

Soldering and Coating

In coating objects such as wire or strip with a molten metal such as aluminum, a finer and more adherent coating is obtained by subjecting the object to vibratory motion before and during immersion in the melt. The technique can be used in continuous processing.

P228. Petermann, L. A. (Gulton Industries, Inc.), "Ultrasonic Soldering Pot." U.S. Patent 2,926,622, March 1, 1960 (filed Aug. 23, 1955).

Ultrasonic apparatus is used to excite molten solder in a pot to cavitation, to effect simultaneous cleaning and soldering of metals such as aluminum and magnesium. The vibrating assembly, which rests on the rim of the pot, consists of an annular transducer of barium titanate or the like excited in its radial mode and coupled by several short rods to an inner ring of fused quartz, which is segmented to relieve thermal and vibrational stresses. The quartz segments are partially submerged in the molten solder.

P229. Alexandraitis, V. U., "A Method for Ultrasonic Soldering of Aluminum and Its Alloys." USSR Patent 133,738, filed March 28, 1960.

Fluxless soldering of aluminum and its alloys is carried out by subjecting the soldering area to ultrasonic vibrations in order to provide more complete elimination of the oxide layer from the aluminum surface. The device consists of a magnetostrictive transducer to which the soldering tip is attached. If desired, a heating element can be installed on the tip.

P230. Carlin, B. (Alcar Instruments, Inc.), "Ultrasonic Soldering Equipment." U.S. Patent 2,951,975, Sept. 6, 1960 (filed May 1, 1956).

This patent concerns a driving unit for an ultrasonic soldering iron wherein a magnetostrictive transducer is excited by means of non-sinusoidal wave energy rather than the usual sinusoidal type. The driving generator incorporates a square-wave multivibrator, a push-pull amplifier, and a phase-inverter coupling these two members, as well as means for coupling the amplifier to the transducer coil to shock-excite the transducer at its natural frequency. It is stated that the resulting ultrasonic output is large relative to the electrical input.

P231. Hanlein, W. and U. Birkholz (Siemens-Schuckertwerke A.G.), "Method of Joining Thermoelectric Components." U.S. Patent 2,978,570, April 4, 1961 (filed July 10, 1959).

Thermoelectric components may be solder-joined by placing a layer or foil of solder between the areas to be joined, subjecting the assembly to mechanical pressure, and passing direct current through to melt the solder. The operation may be intensified by simultaneous application of ultrasonic vibration and/or use of a protective gas atmosphere to avoid oxidation.

P232. Dixon, A. and J. R. Spierto (Westinghouse Electric Corp.), "Brazing Alloy and Ultrasonic Process for Using the Same." U.S. Patent 2,984,903, May 23, 1961 (filed Dec. 6, 1957).

Ultrasonic brazing of metals and alloys is accomplished with a brazing alloy consisting of 2-15% (by weight) Cu, 3-7% P, 2-10% Ag, 45-60% Zn, and 20-40% Al. The braze metal is heated to 700°-950°F, applied to the surfaces to be joined, and vibratorily activated for a few seconds at 9 to 60 kHz. Alternately, the workpieces may be immersed in molten braze metal excited to vibration. The process is particularly applicable to joining enameled aluminum or copper wire conductors without prior removal of the enamel.

P233. Gandil, L. E. C., "Method and Apparatus for Formation of Protective Coatings on Surfaces of Metallic Objects." British Patent 885,686, Dec. 28, 1961 (filed June 30, 1958; priority in Denmark June 28, 1957).

Protective surfaces may be formed on metals using a chemically acting solution which is ultrasonically agitated to accelerate coating formation. The solution is flowed continuously through a container with its opening facing the surface to be treated and with a tight-fitting connection between the surface and the container opening to prevent escape of the liquid.

P234. Jones, J. B. (Aeroprojects Inc.), "Ultrasonic Tool." U.S. Patent 3,029,766, April 17, 1962 (filed May 2, 1956).

This ultrasonic tool involves a plurality of vibration-transmitting members driven by a single transducer and acting in identical fashion, wherein the members are flexible and may be separately manipulated into a variety of desired configurations. The device is illustrated particularly with respect to ultrasonic soldering and permits making multipoint soldered connections simultaneously.

P235. Wilks, P. F. (British Oxygen Company Ltd.), "Treatment of Wire." British Patent 899,959, June 27, 1962 (filed Jan. 19, 1960).

Ferrous rod or wire may be copper-coated by immersion in an acid solution of copper sulfate which is ultrasonically agitated at a frequency of 12-80 kHz. The rod or wire is fed continuously through the solution. The ultrasonic treatment reduces the time for coppering by about one-fifth, thus reducing production costs.

P236. Johns, J. F. (Curtiss-Wright Corp.), "Ultrasonic Soldering System." U.S. Patent 3,084,650, April 9, 1963 (filed July 27, 1960).

The soldering device consists of a solder bath container with an inverted "U"-shaped bottom; oppositely rotating paddle wheels located in the

solder on each side of the inverted "U" in order to urge the solder to form a standing-wave crest in the center of the container; an ultrasonic transducer extending from below into the container hollow to activate the solder in the crest; and a conveyor for transporting the objects through the wave crest with the solderable underside of the objects exposed to the solder.

P237. Dixon, A. (Westinghouse Electric Corp.), "Process of Soldering to a Ceramic or Glass Body." U.S. Patent 3,103,067, Sept. 10, 1963 (filed Aug. 13, 1959).

The patent concerns solder compositions containing up to 10% of an alkaline earth metal (magnesium, calcium, or barium) and the balance including various solder metals, and the use of high-frequency vibrations for applying the solder to refractory metals, ceramics, or glass to produce a highly adherent coating. Vibration in the range of 5-100 kHz is applied for a period of time from 1 to 50 seconds and at an intensity of 100 to 1000 watts per square inch, using an activated soldering tip or soldering bath.

P238. Scarpa, T. J. (International Ultrasonics, Inc.), "Electroacoustic Sandwich Transducers." U.S. Patent 3,140,859, July 14, 1964 (filed Jan. 17, 1961).

The patent is concerned with achieving strong joints between ultrasonic system components in order to avoid energy loss in longitudinally vibrating transducers, wherein the Poisson effect produces substantial radial vibrations, as in an ultrasonic soldering tool. Each surface of the joint between transducer and horn is thoroughly prepared; the ceramic transducer is lapped and ultrasonically cleaned, and the metal surfaces are ground flat, ultrasonically cleaned, and etched. The joint is bonded under vacuum with epoxy resin and reinforced with a stud.

P239. Das, D. K. (National Research Corp.), "Plating Process." U.S. Patent 3,217,405, Nov. 16, 1965 (filed June 27, 1962).

Tin coating of wire is accomplished by passing the wire through a molten tin bath at about 550°C, then through an orifice whose wall is vibrated at 60 kHz and passing the wire back and forth through the orifice to produce a smooth coating, then heating to react the coating with the base metal. As an alternative, a rod may be ultrasonically coated and drawn to wire size, or the tin bath itself may be vibrated during coating.

P240. Voronin, G. I., G. I. Eskin, V. I. Slotin, B. S. Zaretskii, A. I. Krylov, P. N. Shvetsov, and G. I. Barannikov, "Ultrasonic Bath for Soldering Metals." USSR Patent 181,967, April 21, 1966 (filed Jan. 29, 1965).

Soldering and Coating

A solder bath is described which is heated from the sides and ultrasonically excited from beneath. The patent claims that this device increases production rates.

P241. Christensen, F. W. (Western Electric Co., Inc.), "Methods of and Apparatus for Metal-Coating Articles." U.S. Patent 3,277,566, Oct. 11, 1966 (filed March 19, 1963).

The apparatus consists of a reservoir of molten solder through which projects an ultrasonic horn terminating just below the surface of the liquid. The horn is vibrated to cause severe cavitation in the liquid layer above it, producing a cloud of molten solder particles above the melt surface, into which the workpiece is introduced. Oxide films and other contaminants on the workpiece surface are penetrated and a strongly adherent fusion bond is produced.

P242. Patrick, G. D. and K. S. Archibald (General Dynamics Corp.), "Ultrasonic Soldering Apparatus." U.S. Patent 3,303,983, Feb. 14, 1967 (filed Nov. 12, 1964).

A molten solder bath is provided with a manifold into which liquid solder is pumped. The top of the manifold is provided with a coupler unit, extending across the width of the manifold, which contains a central slot. The solder coming up through this slot is set into a standing-wave pattern by an ultrasonic driver transmitting ultrasonic energy through a shaft into the coupler.

P243. Jacke, S. E., E. A. Harris, and F. J. Macalus (Branson Instruments, Inc.), "Ultrasonic Soldering or Plating Apparatus." U.S. Patent 3,385,262, May 28, 1968 (filed Sept. 18, 1964).

An ultrasonic soldering or plating device consists of a molten metal container provided at its bottom or side with an opening through which an ultrasonic horn extends, and a metal reservoir underlying the container. Molten metal is permitted to leak through a small gap between the opening and the ultrasonic horn into the underlying reservoir, thus obviating the need for a tight seal.

P244. Roczey-Koller, K. (Electrovert Manufacturing Co. Ltd.), "Production Line Soldering with Application of Ultrasonic Energy Directing to Molten Solder." U.S. Patent 3,430,332, March 4, 1969 (filed April 1, 1966).

Soldering or tinning is accomplished by passing the workpiece through a standing wave of molten solder while ultrasonic energy is applied directly

to the standing wave through a horn immersed in the standing wave and energized by a transmission member extending through the wall of the solder container. Static pressure is applied to the molten solder in the container to cause the solder to flow upward through an upright nozzle and overflowing the edges of the nozzle to form a standing wave with return of the solder to the container.

P245. Terrill, J. R. and S. F. Dzierski (Aluminum Co. of America), "Fluxless Ultrasonic Soldering of Aluminum Tubes." U.S. Patent 3,680,200, Aug. 1, 1972 (filed Dec. 16, 1970).

Joining of aluminum heat exchanger tubes for air-conditioning and refrigeration units is accomplished by soldering or brazing, wherein the filler metal is melted and caused to flow into the annular gap between a male and female member. Sound joints can be produced by in situ ultrasonic fluxless soldering when the annular gap is maintained at 0.002-0.006 in. The ultrasonic energy is supplied through two prongs spaced to engage opposite outer faces of the joint and is applied in a multidirectional manner.

Wrenching

P246. Pruder, G. D., N. Maropis, and J. B. Jones (Aeroprojects Inc.), "Methods and Apparatus Employing Torsional Vibratory Energy for Wrenching." U.S. Patent 3,521,348, July 21, 1970 (filed Dec. 7, 1967).

Methods and apparatus are described wherein high-intensity vibratory energy in the torsional mode is applied simultaneously with mechanical tightening in the wrenching of threaded fastener connections. The process reduces friction at the mating thread surfaces, increases the degree of preload attainable, reduces torsional stress induced during tightening, improves interference fit performance, effects non-precision tightening, and facilitates removal of bound or jammed threaded fasteners. Various embodiments are described and illustrated.

P247. Maropis, N., W. A. Wilson, and H. T. Blaise (National Aeronautics and Space Administration), "Methods and Apparatus Employing Vibratory Energy for Wrenching." U.S. Patent 3,526,030, Sept. 1, 1970 (filed Dec. 7, 1967).

Method and apparatus are provided for applying ultrasonic energy to mechanical fasteners which are elastically compliant along the radius vector in order to provide improved tightening or loosening of the fasteners. The vibration is introduced essentially along the radius vector of the fastener. Provision is made for tightening the fastener to a predetermined torque level and for applying the vibration while simultaneously rotating the fastener an additional amount without increasing the torque level.

Wrenching

P248. McMaster, R. C. (Ohio State University), "Process for Torquing Threaded Fasteners." U.S. Patent 3,650,016, March 21, 1972 (filed April 28, 1969).

In the torque-tightening of threaded fasteners, vibratory energy is introduced into one end of the fastener while the nut is turned down on the opposite end, so that when the energy is removed, the fastener is left in a state of tension. It is stated that known tension in the assembly is thus established, that force required to achieve a given tension is reduced, and that accuracy of achieving a given tension is increased. Assemblies that have been rusted or seized can be easily separated by reversing the process.

Press Fitting

P249. Balamuth, L. (Cavitron Ultrasonics Inc.), "Method of High-Frequency Vibration Fitting." U.S. Patent 3,224,086, Dec. 21, 1965 (filed Nov. 13, 1961).

A member such as a rod, pin, or shaft may be inserted into a corresponding recess, socket, or bore through the exertion of moderate pressure between the two members and with ultrasonic activation of at least one of the members. The surfaces of the mating members are thus always in relative motion and frictional resistance is reduced so that lower static force is required.

P250. Bodine, A. G., "Method of Sonic Press Fitting." U.S. Patent 3,481,027, Dec. 2, 1969 (filed Jan. 6, 1965).

When two tight-fitting parts are to be forced together by a sliding action along a meeting interface, frictional forces are reduced and sliding action facilitated by delivering sonic energy to one or both parts to cause elastic vibration at the interface. Mentioned examples include fitting a tight-fitting bushing into a hole, pressing a wedge, lid, or part into a slot, a shim between surfaces, a plug into a hole, a gear onto a shaft, etc.

P251. Bayerische Flugzeugwerke A.G., "Process for Electrical Welding." French Patent 844,659, April 24, 1939 (filed Oct. 12, 1938).

Electrical spot or seam welding of light metals or alloys is facilitated by subjecting the metal simultaneously to the action of acoustic vibrations within the range of 500 to 32,000 hertz, using transducers mounted either above or inside one or both welding electrodes. This procedure is reported to improve static and dynamic strength, as well as corrosion resistance, of the weldments.

P252. Hentzen, F. (Messerschmitt A.G.), "Electric Welding Apparatus." U.S. Patent 2,222,906, Nov. 26, 1940 (filed Oct. 10, 1938; priority in Germany Oct. 13, 1937).

A method is provided for spot or seam welding of metals, especially aluminum and its alloys, by electrical resistance welding, wherein high-frequency vibration (at least in the higher audible frequency range) is applied through one or more welding electrodes simultaneously with welding current. The structural properties of the welds are thus considerably improved by thorough mechanical treatment of the weld during welding and cooling.

P253. Schöfer, R. (Siemens-Schuckertwerke A.G.), "Process for Electrical Spot Welding Especially for Aluminum Alloys." German Patent 741,188, Sept. 16, 1943 (filed April 1, 1941).

Electrical resistance spot welding may be accomplished by exciting at least one welding electrode to mechanical vibration in a direction transverse to the longitudinal axis of the electrode. Strong welds are thus produced, and the weld metal structure is substantially improved. Vibratory frequency is preferably between 1000 and 8000 Hz, produced by a mechanically or electrically driven striker or by a magnetostrictive transducer.

P254. Hentzen, F. H. (Messerschmitt A.G.), "Process for Electrical Resistance Welding, Especially Spot and Seam Welding, of Light Metals or Light Metal Alloys." German Patent 745,139, Dec. 2, 1943 (filed Feb. 14, 1937).

Electrical resistance spot and seam welding, especially of light metals and alloys, is carried out under ultrasonic influence. The process is stated to destroy dendritic structure in the weld zone, fatigue strength is improved, subsequent annealing is eliminated, and corrosion resistance of the weld zone is improved.

P255. "Process for Electrical Spot Welding with a Simultaneous Effect of Sonic or Ultrasonic Energy." German Patent 748,193, March 23, 1944 (filed Oct. 14, 1937). (Inventors not designated)

Resistance spot welding is carried out with sonic or ultrasonic activation of one or both electrodes via a transducer installed directly in or on the electrode. With a double acoustic transmitter, the transducers may operate at the same frequency and in the same phase or with a phase difference of about 180°. The ultrasonic power is introduced independently of the electrical in order to prevent disruption of the acoustical transmitter.

P256. Schöfer, R., "Apparatus for Electrical Spot Welding, Especially of Aluminum Alloys." German Patent 748,684, April 13, 1944 (filed Jan. 21, 1941).

The efficiency of an ultrasonically activated resistance spot welder is increased when both electrodes are elastically suspended in the direction of vibration as close as possible to the weld zone. The vibratory appendage for one electrode is shorter and thicker than the other to achieve the necessary mass. Either a striker or a magnetostrictive transducer is used to excite the electrode to vibration.

P257. Ahlert, W. (Elektro-Thermit Essen GmbH), "Production of Fine Structure in the Weld Zone with Materials Welded by the Thermit Process." German Patent 806,857, April 12, 1951 (filed July 8, 1949).

Welding of materials by the Thermit process (wherein a mixture of aluminum and iron oxide powder are heated to 2000°C or higher and thus converted to steel) is accomplished with high-frequency vibration of the weld metal or of the pieces to be joined. This produces a fine grain structure with superior tensile and shear strength.

P258. Becker, K., "Process for Welding or Soldering." German Patent 816,779, Aug. 16, 1951 (filed March 3, 1949).

Finer grain structure, degassing, and higher weld strength are said to be achieved in arc or autogenous welding by the introduction of ultrasonic energy at the edge of the sheet being welded.

P259. Kadlez, K. (Simmering-Graz-Pauker A.G. für Maschinen-, Kessel- und Waggonbau), "Process for Electrical Arc Welding Under the Influence of Sonic or Ultrasonic Vibration." Austrian Patent 171,780, Dec. 15, 1951 (filed April 4, 1950).

Fusion Welding

The advantages of ultrasonic treatment during arc welding (degassification, grain refinement, more homogeneous structure) can be achieved without costly electronic devices by exciting the arc to high-frequency vibration.

P260. Huwyler, O. and J. Rosselet (Spadas A.G.), "Apparatus for Electrical Resistance Welding of Light Metals and Light Metal Alloys." German Patent 839,397, April 10, 1952 (filed Jan. 14, 1950; priority in Switzerland Jan. 25, 1949).

An electrical resistance welding device involving ultrasonic activation of at least one electrode is provided with at least one magnetostrictive transducer of longitudinal shape which has a non-magnetic interface extending the greater part of the length of the member, to prevent transducer breakdown after extended operation. The transducer may be a tubular member with a longitudinal slit, or may have other described geometries.

P261. Kadlex, K. (Simmering-Graz-Pauker A.G. fur Maschinen-, Kessel- und Waggonbau), "Gas Welding." Austrian Patent 171,191, Oct. 15, 1951 (filed March 6, 1950).

Inert gas welding is carried out with the flame of the torch excited to vibration at sonic or ultrasonic frequency. Any type of acoustic generator may be used.

P262. Schöfer, R. (Siemens-Schuckertwerke A.G.), "Welding Apparatus." German Patent 908,649, Aug. 20, 1953 (filed March 13, 1943).

In a spot welding apparatus in which one or both electrodes are excited to vibration during weld formation, ultrasonic transmission into the weld zone is improved when an elastic intermediate member, which may be a copper ring, is inserted between the transducer and the electrode, to prevent distortion of the vibratory resonance in the structure.

P263. Bayha, H. (Siemens & Halske, A.G.), "Apparatus for Influencing Molten Metal During Welding." German Patent 920,387, April 22, 1954 (filed Jan. 6, 1942).

In ultrasonic resistance welding devices, the transducer is attached to a coupler which is exponentially tapered either in a converging or diverging direction which transmits the vibrations to the molten metal. The end of the coupler can serve as the welding electrode. Embodiments are described for a resistance spot welder, a seam welder (utilizing a diverging coupler), and a soldering bath (likewise diverging).

Fusion Welding

P264. Schöfer, R. (Siemens & Halske A.G.), "Welding Apparatus, Especially for Spot Welding." German Patent 921,041, Oct. 28, 1954 (filed Jan. 21, 1942).

A resistance spot welder is provided with a magnetostrictive transducer attached to the head of at least one of the welding electrodes with its axis forming an angle of 20 to 70 degrees with the welding axis. Activation of the transducer (frequency between 3 and 20 kHz) during spot welding effects grain refinement of the weld metal and improves mechanical properties of the joint.

P265. Schöfer, R. (Siemens-Schuckertwerke A.G.), "Apparatus for Electrical Resistance Spot Welding, Especially of Aluminum Alloys." German Patent 921,765, Nov. 18, 1954 (filed Jan. 19, 1941).

An apparatus is proposed for resistance spot welding, especially for aluminum alloys, with vibratory excitation of the electrodes, wherein one of the electrodes is rigidly mounted and the other is elastically mounted via a diaphragm in the vicinity of the weld zone. Thus the weld zone is located in the locale of the vibratory system. In this manner, especially strong welds are produced. A magnetostrictive transducer can be used to generate high-frequency vibration, or a mechanical striker for low frequency.

P266. Esche, R. and L. Pfeifer (Siemens-Schuckertwerke A.G.), "Process for Resistance Welding, Especially Spot Welding, Under Vibratory Influence." German Patent 958,946, June 14, 1956 (filed Nov. 14, 1953).

Resistance spot welding under ultrasonic influence is carried out with the high-frequency vibrations transmitted through a coupling liquid to the weld zone, with the liquid maintained under pressure to prevent cavitation therein. At least one welding electrode is attached to the transducer; the electrode forming the container for the coupling liquid may be tapered conically or exponentially toward the welding tip. A pressure diaphragm attached to the transducer serves as a seal. With this arrangement, none of the sound energy is reflected by an air interspace.

P267. Kaiser, R. G. (Gussolit-GmbH, Hajek & Co.), "Welding Rods from Gray Cast Iron." German Patent 961,633, April 11, 1957.

Inert-gas arc welding is carried out with ultrasonic activation of the welding rod. The apparatus involves a magnetostrictive transducer and coupling member to which the welding rod is attached. The activation produces weld seams of refined grain structure, reduced porosity, and higher strength.

Fusion Welding

P268. Wenk, R. and H. Cammerer (Siemens-Schuckertwerke A.G.), "Process for Resistance Welding, Especially Spotwelding of Light Metals Such as Aluminum, Etc. under the Influence of Ultrasonic Vibrations." German Patent 968,008, Dec. 19, 1957 (filed Dec. 31, 1953).

In resistance spot welding under the influence of ultrasonics, the metal to be welded is acoustically treated under an air seal such as a neutral paste or liquid so that oxide layers are disrupted and can not be re-formed. Subsequently the weld zone is made smooth with a tin coating applied to the surface, likewise under an air seal and under ultrasonic influence. The welding device and the acoustic device may be mounted in a swivel arrangement for cycling.

P269. Johnson, H. R. and J. E. Boyer (Lukens Steel Co.), "Ultrasonic Coupling for Welding Rod." U.S. Patent 2,824,950, Feb. 25, 1958 (filed Nov. 22, 1955).

A welding rod is vibrated longitudinally at 20 kHz by a transducer through an intermediate driving rod. The upper end of the welding rod is supported in a cup recessed in the lower end of the driving member. When the rod is vibrated, molten metal from it is deposited as rapidly as it is melted, thus eliminating the accumulation of large drops that cause short circuits. The welds thus produced have finer grain size and increased strength and corrosion resistance.

P270. Cresswell, R. A. (E. M. F. Electric Company Proprietary Ltd.), "Fusion Welding of Metals." Australian Patent 215,374, June 12, 1958 (filed Feb. 8, 1957).

In fusion welding, particularly gas-shielded electric arc welding of metals, the application of mechanical vibrations in the range of 47 to 25,000 Hz is reported to produce significant effects in terms of oxide film disruption, grain refinement, and degassification. The vibrations may be applied through the work support member, directly to the workpiece, or through the welding torch.

P271. Cronin, E. J., "Ultrasonic Welder." U.S. Patent 2,846,563, Aug. 5, 1958 (filed Oct. 7, 1955).

A resistance welding machine with a pair of electrodes to contact the workpieces has one hollow electrode filled with liquid and containing means for generating ultrasonic vibrations which are transmitted through the liquid to the electrode tip and thence into the metal being welded. The transducer is preferably magnetostrictive, and is activated during passage of welding current to inhibit grain growth in the weld metal. A circulating cooling water jacket prevents the assembly from overheating.

P272. Brennen, R. F. and J. A. Bucci (Welding Industry Research and Patent Corp.), "Method and Apparatus for Breaking up Oxide on, and Welding, Metal." U.S. Patent 2,847,556, Aug. 12, 1958 (filed Sept. 7, 1956).

In electrical resistance welding of materials having oxide coatings, such as aluminum, ultrasonic energy is introduced through both electrodes in light contact with the sheet prior to the introduction of the required welding pressure and current. This effectively disintegrates the oxides and eliminates the necessity for precleaning the weldment material.

P273. Cresswell, R. A. (British Oxygen Co. Ltd.), "Fusion Welding of Metals." U.S. Patent 2,908,801, Oct. 13, 1959 (filed Jan. 28, 1957; priority in Great Britain Feb. 14, 1956).

Gas-shielded arc welding is carried out with vibration (47 to 25,000 Hz) of the weld metal during welding and also during subsequent cooling. Oxide films are thus disrupted and dispersed, metal dendrites are fragmented, and gas removal from the metal is facilitated, thus producing refined grain structure and less porosity in the weld metal. Either the workpiece or the gas supply nozzle may be vibrated.

P274. British Refrasil Company Ltd., "Process and Apparatus for Welding Metal or Alloy Workpieces." French Patent 1,255,670, Jan. 30, 1961 (filed April 26, 1960; priority in Great Britain May 1, 1959).

The welding process consists of vibrating a rod-shaped welding electrode at ultrasonic frequency in the longitudinal direction, applying the electrode with low pressure against the workpiece so that the vibration is perpendicular to the weld interface, and passing electrical current through the electrode intermittently or continuously. The apparatus incorporates a transducer-electrode carriage consisting of a transducer and a spindle-shaped horn, with the welding electrode attached to its lower end. The workpiece is supported on an anvil in which a second electrode is embedded. Force is applied through a flywheel-controlled hydraulic system. The process requires reduced heat, energy, and pressure, and permits achieving improved-quality weldments.

P275. Eaton, N. F. (United Kingdom Atomic Energy Authority), "Improvements in or Relating to Welding." British Patent 875,035, Aug. 16, 1961 (filed Aug. 1, 1958).

The invention concerns a method of direct-current arc welding wherein ultrasonic vibrations are transmitted through a wire, such as piano wire, one end of which may be immersed in the molten region or may be attached to a filler rod so that the vibrations are applied directly to the melt. The result is reported to be refined grain structure and improved mechanical properties in the weld metal.

Fusion Welding

P276. Hill, J. M., "Welding Method Employing Ultrasonic Energy." U.S. Patent 3,101,404, Aug. 20, 1963 (filed Jan. 29, 1962).

In the manufacture of tubing or pipe, wherein metal strip is formed into a cylindrical shape and is heated and welded along the mating edges, a weld bead or burr is formed and must subsequently be removed. It is proposed that the weld be formed by heating the two edges to fusion temperature and introducing ultrasonic vibrations into at least one of the seam edges. The weld is thus produced without substantial upsetting and without the formation of a substantial bead. Oxide impurities are dispersed and grain structure is refined.

P277. Jones, J. B. and N. Maropis (Sonobond Corp.), "Method and Apparatus for Ultrasonic Welding." U.S. Patent 3,201,864, Aug. 24, 1965 (filed Nov. 25, 1960).

A method and apparatus are provided for effecting high-speed fusion welding of tubing, plates, etc., in which an outer face of one of the metal members is contacted with a vibrating element, spaced from the intended weld zone, and capable of being translated along the workpiece as welding proceeds. The melt puddle is located at an antinode of the conducted vibratory energy. The process is said to produce fine, equiaxed grains, minimize cracking tendencies, and produce reliable and reproducible joints. Seam welding of tubes can be accomplished without formation of a substantial weld bead.

P278. Bodine, A. G., "Method and Apparatus for Removal of Insulation Coating of Parts in Spot Welding." U.S. Patent 3,291,957, Dec. 13, 1966 (filed Oct. 12, 1965).

Insulating surface coating can be removed from a metal surface to be welded as an integral part of the welding operation by introducing vibratory energy through one electrode of a resistance spot welder while passing current through the electrode.

P279. Bodine, A. J., "Apparatus for Accomplishing Sonic Fusion Welding and the Like Involving Variable Impedance Load Factors." U.S. Patent 3,439,409, April 22, 1969 (filed March 24, 1966).

In the friction fusion welding of two parts, the parts are supported in contact with one another and vibratory energy is introduced into both members at a frequency slightly below the resonant peak of each. The energy is transmitted to the surfaces to be joined, generating heat at the interface and fusing the parts together.

Fusion Welding

P280. Poulton, C. A. and C. W. Lovellette (McDonnell Douglas Corp.), "Sonic Apparatus for the Irradiation of Weld Fusion Zones." U.S. Patent 3,487,194, Dec. 30, 1969 (filed May 31, 1966).

For fusion welding, an apparatus for sonic irradiation of metallic weld melt zones comprises a tubular sonic horn which is fed with gas under pressure. The air column is vibrated at high frequency and the vibrations reach the weld zone via air coupling. Refined grain structure and improved weld strength are thus obtained.

P281. Seeloff, M. M. (Taylor-Winfield Corp.), "Method of Joining Metal Sheet and Strip." U.S. Patent 3,504,427, April 7, 1970 (filed Dec. 4, 1967).

In joining metal strips by electrical resistance welding, sonic or ultrasonic energy is superimposed on the planishing roller to effect oxide coating removal and provide a swaged joint which is then welded by weld rollers, with or without vibratory energy. A superior joint is thus obtained.

APPENDIX C

DOCUMENTARY SOURCES FOR LITERATURE ON ULTRASONIC METALWORKING

(Generally Covering Period 1935 0 1972)

1. Sonic and Ultrasonic references in Aeroprojects Library, accumulated over the past 25 years.
2. Defense Documentation Center: Requested bibliographies on Ultrasonic Metal Forming, Ultrasonic Metal Removal and Ultrasonic Metal Joining.
3. Technical Abstract Bulletin (Defense Documentation Center)
4. U. S. Government Research Reports (U. S. Department of Commerce)
5. Scientific and Technical Aerospace Reports (National Aeronautics and Space Administration)
6. International Aerospace Abstracts (American Institute of Aeronautics and Astronautics)
7. Review of Metal Literature (American Society for Metals)
8. Metallurgical Abstracts (Institute of Metals, London)
9. Chemical Abstracts (American Chemical Society)
10. Engineering Index (H. W. Wilson Co.)
11. Defense Metals Information Center: Bibliographies
12. Battelle Technical Review (Battelle Memorial Institute)
13. Powder Metallurgy Science & Technology Abstracts (Franklin Institute Research Laboratories)
14. Journal of the Acoustical Society of America: Articles and Bibliographies
15. Ultrasonics (Iliffe Industrial Publications Ltd., London): Articles and Bibliographies
16. Soviet Physics--Acoustics (Cover-to-cover translation of Akusticheskii Zhurnal): Articles and Bibliographies
17. Acustica (S. Hirzel Verlag, Stuttgart, Germany): Articles and Bibliographies

18. Russian Ultrasonics (Translation of selected Russian papers; Multi-Science Publishing Co. Ltd., Essex, England)

19. L. Bergmann, Der Ultraschall, 6th Edition (S. Hirzel Verlag, Zurich, Germany, 1954): Bibliographies

20. R. Pohlman, Documentation in Ultrasonics, Vol. I-IV (Laboratorium fur Ultraschall, Rheinisch-Westfalisch Technische Hochschule, Aachen, Germany, 1965-1971)

21. Henry Brutcher Technical Translations (P. O. Box 157, Altadena, California)

22. British Iron & Steel Industry Translation Service, London

23. Technical Translations (U. S. Department of Commerce)

24. Official Gazette of the United States Patent Office

25. Bibliographies and references cited in pertinent documents.